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GEOLOGY OF VENEZUELAN ANDES[1]

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ABSTRACT

The Venezuelan Andes, considered as a geologic unit, has a special interest structurally as the abrupt and massive bulkwark between the Maracaibo basin and the Orinoco plains, from the lowlands of which, at 100 and 200 meters, respectively, it rises to the maximum of more than 5,000 meters on the snow-capped peaks. Though the bulk of the mountain mass is composed of Paleozoic or older metamorphic rocks, including some fossiliferous Carboniferous, sediments ranging up to Cretaceous are found at 3,000 meters, 4,000 meters, or even higher, and Eocene rocks occupy large areas in the southwestern portion. Topography, areal geology, and structure sections are shown on maps, and serve to indicate broad lines of structure. It is a great geanticline without boundary faults at the present mountain fronts, cut by cross faults which further work may show to be of greater rather than of less importance. Present evidence indicates that classic Alpine structural concepts are not applicable to the isolated problem of the Venezuelan Andes.

Carboniferous localities not heretofore published are mentioned and further discoveries predicted. Cretaceous rocks are mapped in new areas, and the Cretaceous-Eocene unconformity is shown to be of minor importance as a structural break compared with unconformities at the base of the Cretaceous and in Middle Miocene.

INTRODUCTION

The name "Venezuelan Andes" is applied to that spur of the Andes which trends northeast through the states of Táchira, Mérida, and Trujillo, in Venezuela. On the northwest is the Maracaibo Lake basin with its swamps and on the southeast the Orinoco River basin with its broad llanos. This Andean spur is separated from the Colombian highlands (Sierra Oriental) by a saddle in Táchira, and on the northeast it again plunges down and merges with the west-east trending

[1] Manuscript received, February 25, 1935. Published by permission of the Venezuelan Atlantic Refining Company.

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Coast Ranges, or Caribbean range of Sievers, from which it differs in several respects first pointed out by Sievers.[3]

The most complete geologic map and the best description of the geology and structure of this mountain unit were written by Sievers, and published 46 years ago. This map was used in the preparation of the map of North America in *Professional Paper 71* of the United States Geological Survey, and for that reason the latter gives a truer picture of areal geology than the map of Liddle,[4] based on very few reconnaissances because at that time oil companies had done little work in the Andes. More recently de Cizancourt[5] has ably synthesized the tectonics involving this and other spurs of the Andes north of the "Peruvian Knot."

Acknowledgments

The writer, during nearly 6 years (1925–31) of study in Venezuela (approximately one year in eastern Venezuela, 3 years in the north Maracaibo basin, and 2 years southeast of Maracaibo Lake), had the privilege of making several trips across the Venezuelan Andes. This work was done for the Venezuelan Atlantic Refining Company, and thanks are due to this company through its vice-president, W. M. O'Connor, and its chief geologist, R. E. Dickerson, for permission to publish the present paper.

For a brief but interesting period W. H. Butt, W. D. Chawner, and Donald McArthur coöperated in study of the northwest mountain front. During 16 months spent in semi-detailed survey of the southeast mountain front, R. E. Crist was associated with the writer.

Culture

The heavy rainfall, good drainage, relative accessibility, and rich and varied soils have combined to make the Venezuelan Andes the most favored region of Venezuela. Wheat, potatoes, and other crops are grown in the highlands at elevations of 3,000 meters (10,000 feet) and higher, and are mainly consumed locally. At 1,000 meters and lower, excellent coffee, the famous "caracolillo," is grown as the main cash crop and most is exported through Maracaibo. Second as cash crop is cacao (cocoa), now mostly grown in the Maracaibo lowlands adjacent to the mountains. The Andes region is the most densely populated in the country, although even here there is much virgin forest and unoccupied territory. Venezuela as a whole has a popula-

[3] W. Sievers, "Die Cordillere von Merida," *Penk's Geogr. Abh.*, Bd. 3 (Wien, 1888). Private English translation by William E. Aitken and Franz Ehm, Maracaibo, 1928.

[4] R. A. Liddle, *The Geology of Venezuela and Trinidad* (Fort Worth, 1928).

[5] Henry de Cizancourt, "Tectonic Structure of Northern Andes in Colombia and Venezuela," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 17, No. 3 (March, 1933).

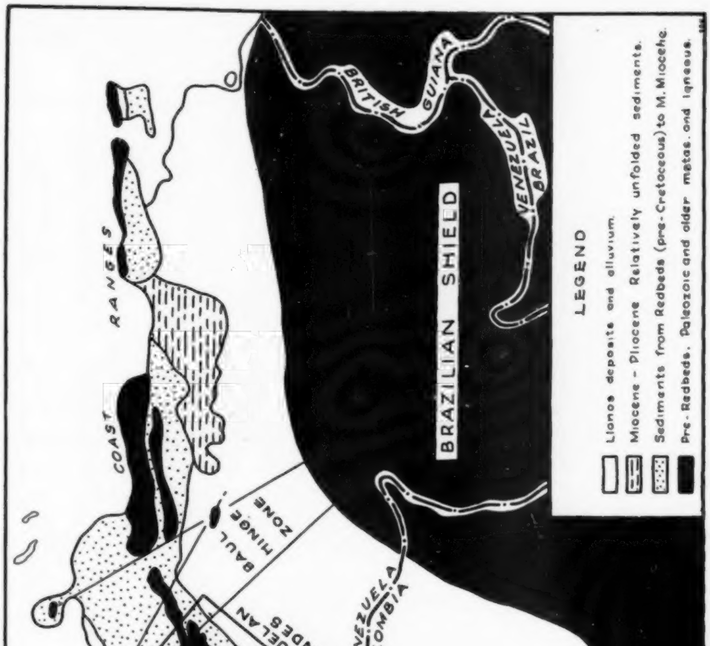

FIG. 1.—Relation of Venezuelan Andes to major features of northern South America. $1\frac{3}{16}$ inch = 200 miles.

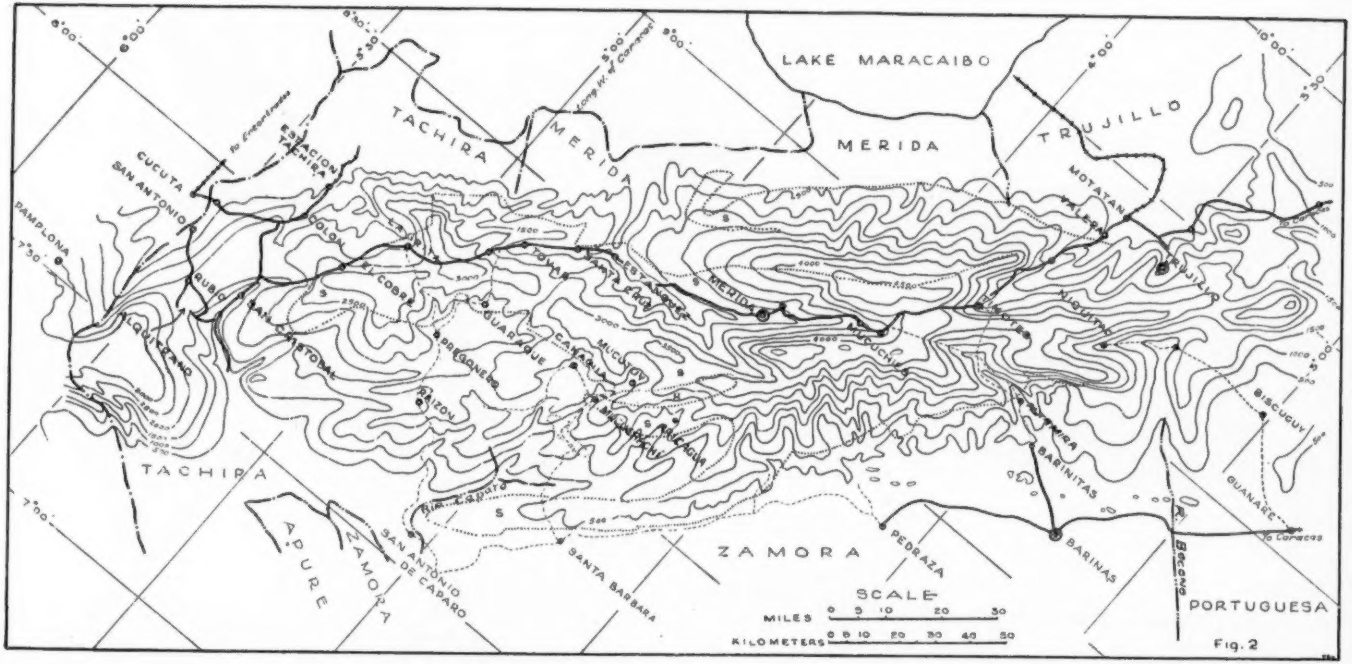

FIG. 2.—Topography of Venezuelan Andes. Contour interval, 500 meters (1,640 feet); datum, sea-level.

tion density of 8.1 per square mile, one-fifth that of continental United States.

In colonial days cities and wealth tended to concentrate along the mountain fronts, the meeting place of agriculture in the mountains and cattle-raising in the Orinoco plains. The succession of revolutions initiated by independence in the early 1800's and culminating in the destructive civil war of 1865, with the disturbances lasting until 20 years ago, subjected these vulnerable points to repeated pillage. Important towns have been actually lost and taken by the jungle, and those remaining are shells in which a few discouraged inhabitants have almost ceased their struggle to rehabilitate abandoned haciendas once devoted to cacao, indigo, coffee and the rich variety of crops which grow so abundantly.

The Andes region is famous in the lowlands for the health of its inhabitants. The climate is invigorating, but probably most of the improvement in health noted in the population over that of near-by regions is due to the richer and more diversified diet available. Susceptibility to malaria in the plains may be increased by malnutrition. As to beri-beri, common south of the Orinoco where all food is shipped in, it is not unknown in the towns between the Orinoco and the Andes, where fresh vegetables could be but are not generally grown.

Until 1932 automobile traffic from Caracas to Táchira and to Pamplona, Colombia, followed the main Transandean Highway (Figs. 2, 3, 4) in part traversing the higher parts of the Andes, with a few side-roads making any part of the mountains accessible with the maximum of 3 days of mule travel. It is understood that parts of this highway are now impassable and it is closed for through traffic, which is routed at favorable seasons of the year along the southeast mountain front in the state of Zamora. Mule trails cover most parts of the mountains, although even the better trails tend to be dangerous, especially on the suspension bridges over the deep gorges and the fords of the larger rivers.

Topography

Rising from about 100 meters above sea-level on the Maracaibo side and 200 meters above sea-level on the Orinoco side to more than 5,000 meters, nearly 17,000 feet, on the snow-capped peaks, the Venezuelan Andes furnish contrasts in climate, vegetation, and geology unique among accessible mountain ranges in the Western Hemisphere. Figure 2 generalizes the physical features of the region. Contours are adapted from Jensen's map[6] (with additions from barometric observa-

[6] T. Jensen, *Topographic and Oil Concession Map of Northern Venezuela, Revised to April, 1928* (Caracas).

tions by the writer), which in turn are derived from unpublished survey data of Alfredo Jahn of Caracas, who has contributed so much as a pioneer to the geography, anthropology, ethnography, and geology of his adopted country.

Drainage

Rivers are the main recourse of the geologist along the mountain fronts, yielding both a thoroughfare through the jungle, difficult though it may be, and outcrops. Where they cut the mountain front sediments, therefore, they have been intensively surveyed, but less is known of their courses in the plains and the high mountains. Much of the existing information on drainage as it is found on government maps is shown on Jensen's map, but the only published map showing physical features with considerable accuracy is that of Crist.[7] This only treats of the southeast mountain front area between the rivers Caparo and Boconó. The extraordinary close spacing of important streams is shown by the fact that 29 streams are mapped in this 210-kilometer sector, as here listed.

River Caparo	(1)[8]	San Antonio de Caparo
River Otopum	(26)	
River Suripá	(23)	(Mountain front portion)
River Santa Barbara	(14)	Santa Barbara
River Pedraza la Vieja	(20)	
River Currito	(18)	
River Capitanejo	(21)	
River Quiu (or Mene)	(12)	
Quebrada Chameta	(28)	
River Zapa	(22)	
River Michai	(16)	
River Batatuy	(17)	
River Socopó	(9)	
River Bumbum	(10)	
River Minanon	(25)	
Quebrada Barandaca	(27)	
River Acequia	(7, 8 below Ticoporo)	Pedraza
River Ticoporo	(24)	Pedraza vicinity
River Canaguá	(5)	Pedraza
River Curbatí	(13)	
River Paguey	(4)	
Quebrada Caramuca	(29)	
River Santo Domingo	(3, 4 below Caipe)	Barinas
River Caipe	(6)	Barinas
River Yuca	(19)	
Quebrada Barrancas	(29)	
River Masparro	(11)	
River Boconó	(2)	Zamora-Portuguesa state boundary

Distributaries and complex braiding are present at the mountain front where the gradient is suddenly decreased, and some of the cases of stream capture are described by Crist.

[7] R. E. Crist, "Along the Llanos-Andes Border in Zamora, Venezuela," *Geog. Review* (New York, July, 1932).

[8] Numbers refer to relative size rating, 1 being largest, 2 next largest, et cetera.

A confusingly large number of well developed terraces break the steep slopes of the deep gorges of the mountain interior, and will give an interesting study to future generations of physiographers.

Glaciation

The highest peaks near Mérida are always snow covered. According to Jahn[9] the snow descends on occasions in the rainy season to 3,600 meters or lower on the Sierra Culata or Sierra del Norte, and on Sierra de Mérida has been known to reach the timber line at 2,800 meters. The snow melts rapidly and only the higher peaks of the Sierra de Mérida, first to receive the moisture-laden northeast trade winds, support small glaciers at present. Jahn finds that during the past century the glaciers have diminished in size. Pleistocene glaciation, as evidenced by roches moutonées, lakes, and other phenomena, Jahn believes to have reached down to 3,500 meters, with a thickness of glacial ice of 100–125 meters above this elevation.

Geology

Although the University at Mérida is older than most universities in North America, the geology of this well defined and relatively accessible mountain range has been little studied, even by oil companies, except for some detailed work in the parts of the mountain fronts more obviously pertinent to oil and gas possibilities. As to published information on the Venezuelan Andes, little has been added to the literature since Sievers. Besides the references already given, Peter Christ,[10] W. P. Woodring,[11] and W. F. Jones and W. L. Whitehead[12] have thrown light on isolated areas.

An adequate treatment of the Venezuelan Andes would be of value not only to students of South American geology, but to students of mountain structure and isostasy everywhere, for (1) it is a definite unit dropping precipitously both northwest and southeast into flat plains and plunging topographically and structurally at its two ends, and (2) there seems to be a supply of recognizable sediments sufficient to solve the very striking anomalies of structure.

[9] A. Jahn, "Observaciones glaciológicas en los Andes Venezolanos," *Cultura Venezolana*, Año 8, No. 64 (Caracas, June, 1925).

[10] P. Christ, "La coupe géologique le long du chemin de Mucuchachí á Santa Barbara dans les Andes Venezueliennes," *Eclogae geol. Helv.* (1927). A review by C. M. Zimmerman is in *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 12, p. 1123 (1928).

[11] W. P. Woodring, "Marine Eocene Deposits on the East Slope of the Venezuelan Andes," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11, No. 9 (September, 1927), p. 1023.

[12] W. F. Jones and W. L. Whitehead, "Cretaceous-Eocene Unconformity of Venezuela," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13, No. 6 (June, 1929), p. 617.

Unfortunately the present writer can do little more than outline the problem and point out the interesting implications of its solution.

Stratigraphy

PALEOZOIC AND OLDER

Until Peter Christ's valuable work, it was thought that little could be done in the age relations of the generally metamorphosed rocks which form the core of the Venezuelan Andes. The fossiliferous Paleozoic rocks first described by Christ,[13] since found by others in various parts of the mountains distant from this locality, together with considerable suggestion of structure within the slate-schist areas; suggest the possibility of working out a reasonable sequence. It is true that Christ outlined such a sequence, but since his divisions below the Carboniferous seem to be based on evidence of unconformities rather than on fossils, and since these unconformities are in a restricted area which the writer did not have the opportunity to study in such detail as did Christ, the writer is unable to comment on his sequence as a whole.

These rocks are all included under *S* (Fig. 3), with the schists, slates, and igneous rocks. In the present state of knowledge, and with the small scale of the map, the incomplete data for areal differentiation of granites, basic igneous rocks, metamorphics, fossiliferous sediments, are largely omitted, except for some indications on cross sections (Fig. 4).

IGNEOUS

Igneous rocks of many varied types are present, and were described in great detail by Sievers. He pointed out the absence of the eruptives (tuffs and breccias) forming the conspicuous basal part of the Red-beds in the Motilon Range (Sierra Oriental of Colombia), and drew some conclusions as to the distribution of igneous rocks.

Granites are conspicuously valleyforming in contrast to the resistant basalts, gneisses, and slates, under tropical conditions, and hold up rounded crumbling hills only when flanked by clastics or schists of the softer varieties.

SCHISTS AND SLATES

Metamorphic rocks (schists and slates) occupy the greater part of the territory labelled *S* (Fig. 3). The generally micaceous schists occur in great variety, and at some places seem to be only slightly metamorphosed (Fig. 4). The slates are black and are very widely distributed, especially in the central parts of the mountains. They are commonly

[13] P. Christ, *op. cit.*

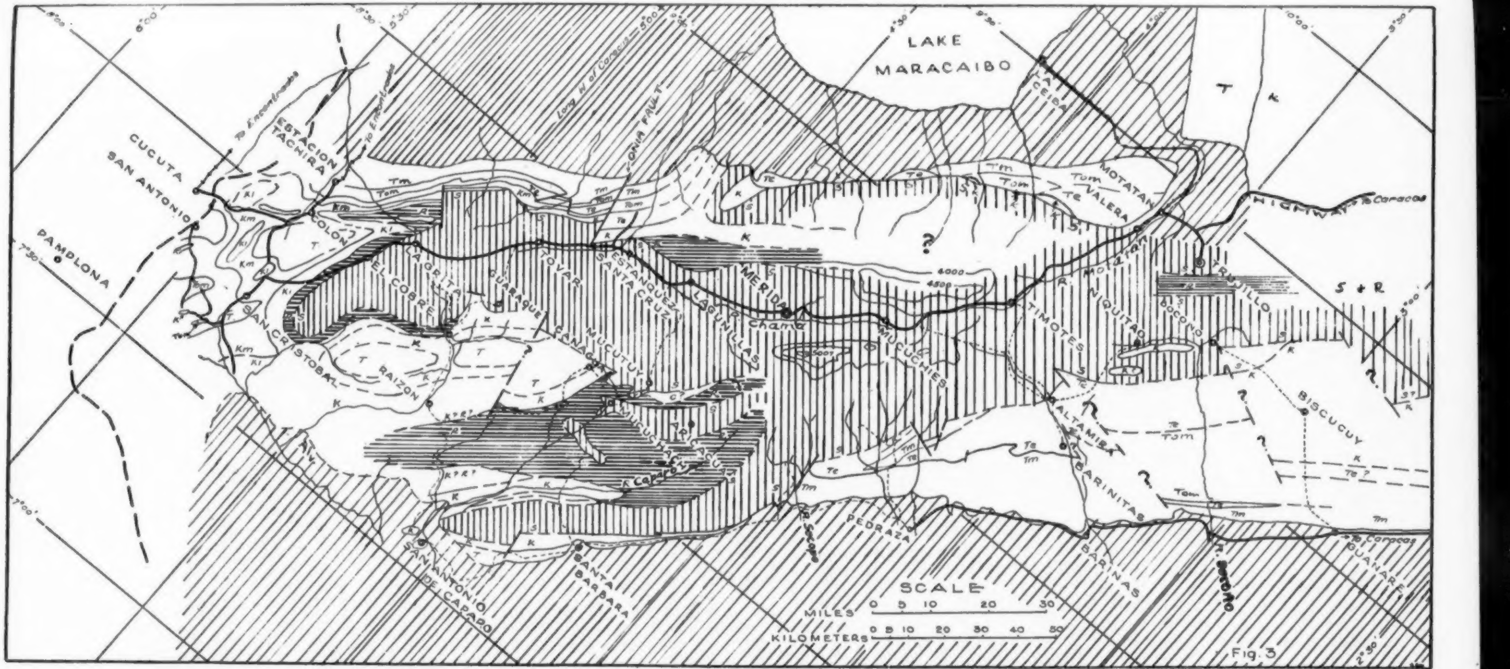

FIG. 3.—Areal geology of Venezuelan Andes.

LEGEND

CENOZOIC	
L, Alv	Pleistocene to Recent, may include also Upper Miocene and Pliocene
Unconformity	Close of Andean revolution, end of active compression, foundering of ill-adjusted fault blocks
T	Tertiary undifferentiated (before Middle Miocene). Thickness ranges to more than 15,000 feet
Tm, Tom	Oligocene? and Lower Miocene
Te	Eocene
Disconformity	Local angular unconformity

MESOZOIC	
K	Cretaceous undifferentiated
Km	Cogollo, La Luna, Colon shale
Kl	Barranquin sandstone
?Unconformity?	
K?R?	Sandstones, may be Cretaceous or Red-beds
PALEOZOIC	
?Unconformity?	
R	Red-beds (Permo-Trias?)
Great Unconformity	
C	Carboniferous (Fig. 4)
Unconformity	
ARCHEAN?	
S	Schists, slates, gneisses, granites, basic igneous rock

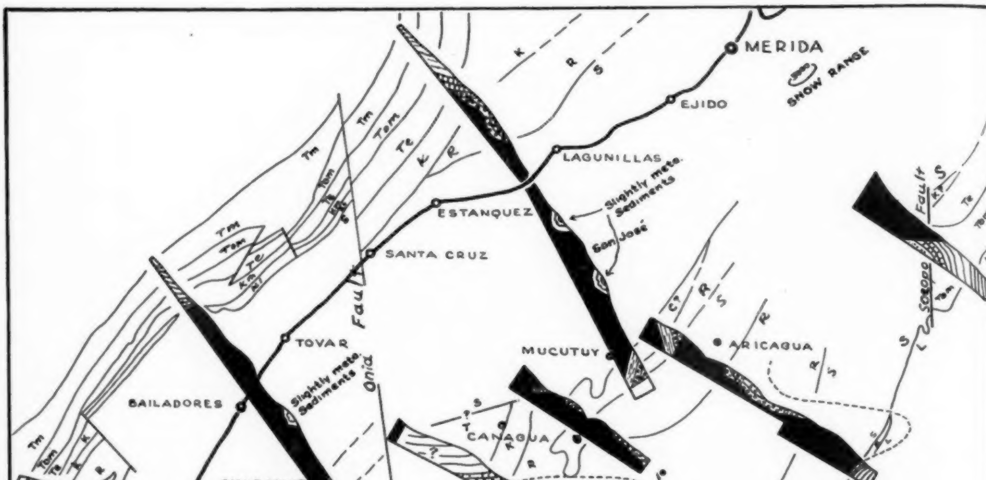

FIG. 4.—Structure sections in part of southwestern Venezuelan Andes.

of such a character that the observer is continually examining them for such fossils as graptolites, hitherto without success. Where they are found at one point (River Batatuy in Zamora) unconformably below a late Tertiary sediment, they have even been mistaken by geologists for Cretaceous black shales, which are commonly barren of megascopic fossils, but in their usual development they are unmistakable. Beds of this character, "black argillaceous schists, in places calcareous or siliceous," compose the "Mucuchachi series" of Christ, which he assigned to the Archean and considered the Basement complex. His "Caparro-Bellavista series" consists mainly of "schists ranging from sandy and mica schists to argillaceous, quartzite schists." They overlie the "Mucuchachi series" unconformably, he states, and are Lower Paleozoic, with a thickness of 3,000 meters. The writer has not seen very definite evidence of these relationships, but as outlined they are not incompatible with the general areal distribution and the few reliable dips mapped in other areas.

UPPER PALEOZOIC

P. Christ assigns his "Mucupatí series" to the Devonian[14] and gives them a thickness of 1,200 meters. They are unconformable over the two formations just mentioned, he states, but definite fossil evidence is not cited. The writer did not have time at his disposal for a search for the type locality of these beds, and is not competent to comment on their age or their relations to the overlying "Palmarito series." Christ gives the latter beds a thickness of 300 meters, and states that they are in places unconformable with the Mucupatí series and in places conformable. The Palmarito is definitely Carboniferous on the basis of fossils identified as *Fenestella*, *Productus*, some gastropods and small trilobites. It is believed that this corresponds with the shales, marls, and limestones observed by the writer in this area, as well as near El Cobre and at certain other points (Fig. 4).

The Transandean Highway (Carretera Trasandina) to Caracas, between San Cristóbal de Táchira and El Cobre, follows the topography back and forth along the strike of the Lower Cretaceous sandstones, working gradually down in the section until the Red-beds are reached. Near the village of El Cobre, after crossing a high divide, it crosses into the older rocks. At first these are metamorphic rocks, but just above El Cobre, at an elevation of about 10,000 feet, there are fossiliferous marls and limestones with etched-out crinoid stems and

[14] Liddle mentions the Devonian encountered between the Red-beds and the igneous in some of the rivers west of Maracaibo, in the Perijá Range (east slope of Sierra Oriental of Colombia). This is the only area in Venezuela outside the Andes where authentic Paleozoic rocks have been identified.

other fossils. From the marls well preserved brachiopods, corals, gastropods, and other fossils weather out and may be picked up near the road.

Similar beds were found at two points south of La Grita (Fig. 4).

Woodring[15] mentions "*Productus*-bearing Carboniferous float" northwest of Barinas, but no report of Carboniferous in place so far northeast is known to the writer. The presence of such float, however, is conclusive evidence that it is present in some part of the highlands of Trujillo, and supports the belief that more detailed work will clarify many of the stratigraphic problems of the Andean complex.

CARBONIFEROUS-TO-CRETACEOUS INTERVAL (PERMO-TRIAS? RED-BEDS)

The rocks already described constitute the core of the Venezuelan Andes, and occupy much of the highlands. However, they are found cropping out at levels of 250 meters and less above sea-level, as in the rivers west of Pedraza in Zamora, as well as on the highest peaks. On the other hand the younger Red-beds, or Lagunillas conglomerate, now to be described, are found in numerous places above 3,000 meters, and are more extensively distributed than has been generally recognized since Sievers.

The Lagunillas conglomerate of Sievers is identical in character and position with the same author's Red-beds[16] of the Perijá Range (Sierra Oriental of Colombia), and probably with a part of the Jiron group of Colombia, which Anderson[17] believed to be Cretaceous. A thin section of Red-beds caps the mountains in the immediate vicinity of Mucuchachí and southward, and these Red-beds were called the "Lomita series" by Christ,[18] who thought they were Lower Cretaceous with the basal part possibly Permian. Sievers pointed out their resemblance to the Devonian Old Red of Europe, but inclined to a late Paleozoic or early Mesozoic age.

The most conspicuous members of the formation are deep red sandstones and resistant red conglomerates, but much of the formation where it is most thickly developed consists of softer sandstones and silts in mottled reds and whites. It thus suggests conditions of sedimentation similar to those that prevailed during the deposition

[15] W. P. Woodring, *op. cit.*

[16] W. Sievers, "Die Sierra Nevada de Santa Marta und die Sierra de Perijá," *Zeit. d. Gesell. f. Erdk.*, Bd. 23 (Berlin, 1888). Private English translation by R. Engleman and J. A. Wilson, Maracaibo, 1928.

[17] F. M. Anderson, "Original Source of Oil in Colombia," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10, No. 4 (April, 1926), p. 382.

[18] P. Christ, *op. cit.*

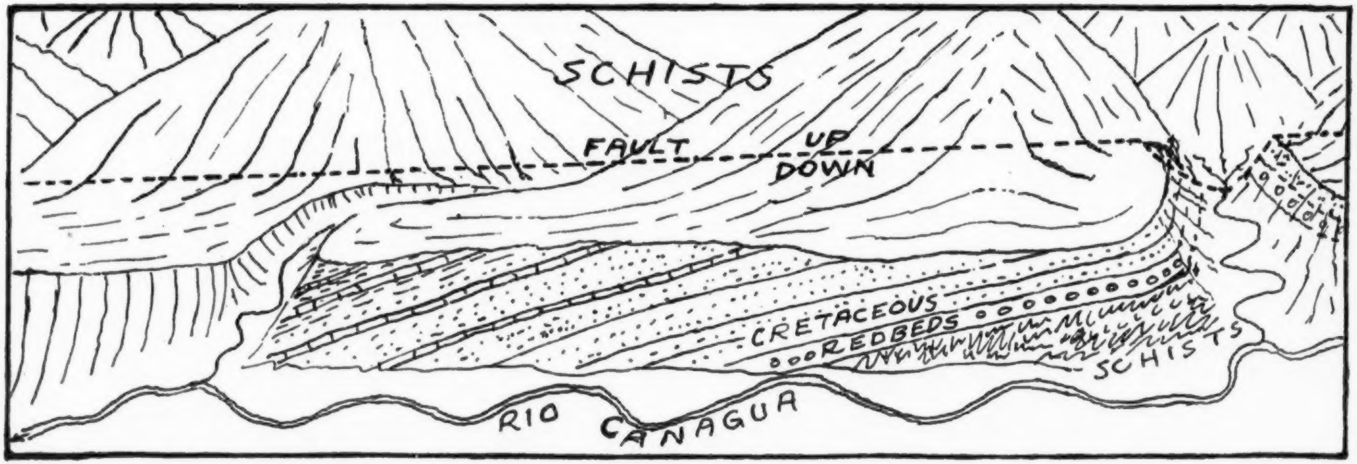

Fig. 5.—Sketch of cliff face on north bank of River Canaguá, from trail between Mucuchachí and Canaguá (Libertad). Red-beds contain boulders of Carboniferous limestone, found in place to southeast, south of Mucuchachí. Possible disconformity between Red-beds and Cretaceous sandstones (Barranquin). Strata strike due north. Elevation at river level more than 8,000 feet; mountains on north in background rise to 15,000 feet; peaks on south may reach 12,000 feet.

of the late Tertiary in Venezuela, in the concluding phases of the Andean revolution, and later.

This parallel in conditions of sedimentation has been noted in other parts of Venezuela. Northwest of Maracaibo the Red-beds (locally called the Pañocira) on outcrop seem to be mainly a deep red color, but where they have been cored in wells 20 kilometers southeast of the outcrop in Manantiales Mountain (north tip of Perijá Range), lying normally below Cretaceous limestones, the cores are strikingly similar to cores from the "Mottled clays" (upper Miocene-Pliocene), in the same area.

A paleogeographic map of Red-beds distribution, constructed from data from wells (including one on Paraguaná Peninsula), would show this to have been a time of widespread deposition of clastics in western Venezuela during the erosion of mountain folds brought up in the late Paleozoic and/or early Mesozoic. East of the northeast end of the Venezuelan Andes and of Paraguaná Peninsula this formation has not been recognized. There is a possiblity, however, that the sandstone capping Mount Roraima in little explored southeastern Venezuela (Brazilian shield), may belong to this period rather than to the lower part of the Cretaceous, to which it has usually been referred.

The thin section of Red-beds (Lomita series) described by Christ thickens tremendously northeast, southeast, and southwest of the Mucuchachí vicinity, and especially southwest.

In the general area of Mucuchachí, the basal part of the Red-beds contains boulders and cobbles of Paleozoic limestone.

A few kilometers northwest of Mucuchachí, in the valley of the River Canaguá 5 kilometers upstream from the village of that name (also called Libertad), a very interesting cliff face is seen on the north bank (Fig. 5).

At this point a thin (about 100 meters) section of Red-beds overlies the highly contorted schists and dips 12° W. Above this in the cliff there is a suggestion of disconformity and then a series of light brown to white sandstones, which contain calcareous ledges with some fossils, probably of Cretaceous age. The dip increases westward, and in traveling southwest toward Canaguá one goes up a characteristic Cretaceous section of dark shales and limestones with typical fossils. The strike swerves westerly (Fig. 4) toward the south. South of Canaguá the trail crosses into the Eocene sandstones dipping northwestward, but soon returns to the Cretaceous and remains therein for nearly 2 days' journey southwestward, until suddenly faulting juxtaposes the Red-beds (Fig. 4).

A short distance north of the cliff face a dip fault, well defined in

the topography, raises the metamorphic rocks to abut the gently inclined younger sediments, as shown in Figure 4.

The Sierra Culata or Sierra del Norte is a long ridge northwest of the gorge of the River Chama (on a high terrace of which the city of Mérida is situated), almost as high as the Snow Range or Sierra Nevada southeast of the gorge. The foot of the ridge adjacent to Mérida is composed of schists and igneous rocks of the Andean complex, like the Sierra Nevada, but since Sievers no one has described the heights of this ridge. Far down in the foothills on the Maracaibo side oil-company geologists have mapped the narrow strip (Fig. 3) of sediments abutting the "igneous," as they crop out in the numerous rivers, but their interests never carried them far up into the mountains beyond this contact, usually recorded as a fault. According to Sievers, it would appear that this igneous rock does not extend far up the mountainside, for he states that almost all the crest of the ridge is made up of Red-beds, with the Cretaceous in succession on the northwest slope. Though the writer has only crossed this ridge at the low point near Lagunillas where Sievers' type section of the red conglomerates is exposed, his experience with Sievers' judgment in other parts of the mountains leads him to believe that this is indeed the case, and that the igneous rock (and schists) near the northwest foot of the ridge occurs in faulted strips and blocks. However, for lack of any guide for reconnaissance formation boundaries, most of the Sierra del Norte is left undifferentiated on the map (Fig. 3).

MESOZOIC

The Red-beds may be in part Jurassic or Triassic, but no beds of this age have been identified in northern South America, and no fossils of any kind have been found in the Red-beds.

CRETACEOUS

Contrary to an impression derived from the fact that three lithologic units are commonly present in the various sections of Cretaceous in northern South America, (1) a black shale increasing downward in calcium carbonate content, (2) massive limestones, and (3) lower sandstones, the Cretaceous is very variable in thickness both of its component parts and in its entirety, and the three lithologic phases, and the faunas of the first two, overlap considerably. The last two may be entirely missing as definite units. On the other hand, the writer knows of no point which has been closely studied where the Cretaceous is entirely missing except by faulting or by overlap of late Tertiary sediments, so that wherever Lower Tertiary is found the Cretaceous underlies it unless faulting obscures relations. The Cre-

taceous seems to be overlain by Eocene with local nonconformity, although the only clear case of this is at Algodones,[19] which the writer has had no opportunity to examine. In those of the many sections mapped by the writer in eastern Venezuela, the Maracaibo basin, and the Venezuelan Andes, where relations were unequivocal, there was no evidence of angular unconformity and no hint of basal conglomerate, and in eastern Venezuela particularly, the Eocene becomes so carbonaceous near the base and the black shales so silty near the top of the Cretaceous that an impression of gradational contact rather than unconformity is obtained. Of course this does not subtract from the time interval which must have elapsed to allow for the great change in fauna between the Cretaceous and the Eocene, but merely suggests that for most of Venezuela the time was one of quiescence, with only a few isolated spots subjected to folding, at least in those areas of the mountains where the Cretaceous is now exposed to our view.

The following classification is taken from Liddle,[20] the first to discuss the Cretaceous in Venezuela comprehensively, and Hedberg.[21]

4. Colon shales (has been used in unpublished work to include La Luna in Venezuelan Andes, but not recognized herein)
3. La Luna formation (Guayuta of Liddle in eastern Venezuela)
2. Cogollo limestone (Cachirí locally in Maracaibo, Punceres of Liddle in eastern Venezuela)
1. Barranquin sandstone

1. *Barranquin sandstone.*—This member seems to be missing in the Barinas segment of the southeast mountain front, although faulting cuts out the entire Cretaceous in many places and it is not certain whether it is present or not. Farther southwest in Zamora, where faulting is not present, a thin section with a maximum of 100 meters is found. Here its base is a definite basal conglomerate. Still farther west and southwest it thickens and becomes an important mountain-forming element in Táchira. Several thousand feet of light-colored

[19] W. F. Jones and W. L. Whitehead, *op. cit.* Referring to specific areas as mentioned in their paper, on which the writer may venture an opinion: in the case of *b, d, e,* and *f,* angular unconformity is either admittedly not present or is an unnecessary interpretation. In the Pregonero area, *g, h,* and *i,* a varying thickness of the Cretaceous is found below the Eocene, notably on the trail about 3 kilometers north of Pregonero, with the possible exception of the area just south of Guaraque, where the presence of an unobserved attenuated section of the Cretaceous is not excluded. Near Canaguá, *j,* the Cretaceous is certainly present between the Eocene and Red-beds, as described herein. Localities *l* and *m* are not conclusive. As to *o,* throughout 30 kilometers of mountain front west of Maturin, regular folding shows no evidence of angular unconformity between the Cretaceous and Eocene; opposite Maturin a faulted situation makes structure more complex, but the writer saw no angular unconformity.

[20] R. A. Liddle, *op. cit.*

[21] H. D. Hedberg, "Cretaceous Limestone as Petroleum Source Rock in Venezuela," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 3 (March, 1931), p. 229.

sandstones in which oysters believed to be lower or middle Cretaceous[22] are found, occur along the highway between San Cristóbal de Táchira and El Cobre, and at other points marked *Kl* (Fig. 3). Even greater thicknesses of sandstone which may be of this age are found in the wide, gently folded sedimentary area north of San Antonio de Caparo and south of Pregonero, but because of doubt as to their age,[23] and difficulty of close separation from the underlying Red-beds, they have been marked *K?R?* on the map (Fig 3).

2. *Cogollo limestone.*—This part of the Cretaceous, in some areas of Venezuela conspicuous though nowhere of great thickness, is variable in thickness and apparently discontinuous in the Andes, so that its massive limestones with their characteristic *Exogyra* become only a phase between the gradational La Luna above and the likewise gradational Barranquin sandstone below. This gradational condition is also noted west of Maracaibo, as shown in cores from Vemor well of Venezuelan Atlantic Refining Company cited by Hedberg,[24] and in eastern Venezuela.

In only two places have beds of this character been found in place on the Zamora (southeast) mountain front—on the River Pedraza la Vieja, 18 kilometers northeast of Santa Barbara, and on the River Quiu (Mene), 40 kilometers northeast of Santa Barbara. In the River Quiu,[25] ledges aggregating less than 3 meters in thickness are found, within 100 meters of the contact between the basal conglomeratic sandstone (Barranquin equivalent) and the metamorphic rocks, the Red-beds being missing (Fig. 3).

Float indicates its presence somewhere upstream on the rivers Bumbum and Minanon, southwest of Pedraza, but the wide belt of Tertiary at this point (Fig. 3), coupled with difficulties rather greater than usual in man-packing far enough up these streams, had prevented its discovery in place up to 1931. The sedimentary section up to the metamorphic contact both northeast and southwest of these rivers shows the Cogollo limestone absent, through faulting or nondeposition or both.

In the remainder of the mountain area the massive light-colored *Exogyra* limestone is found sporadically.

[22] Floyd Hodson, oral communication.

[23] R. E. Dickerson, however, inclines to the belief that certain fossil casts and molds too poorly preserved for identification have a Cretaceous aspect.

[24] H. D. Hedberg, *op. cit.*

[25] The vertical limestones are covered with moss and are entirely below the water surface at low stage. They could easily be overlooked, as it was necessary to chip pieces laboriously with an ordinary pick under several inches of water.

3. *La Luna formation.*—The La Luna formation consists of black thin-bedded-to-laminated calcareous shale or shaly limestone, with occasional ellipsoidal calcareous concretions erratic in distribution laterally but where present increasing in number and size toward the base, where also ledges of limestone of Cogollo character are found. In some places, as in western Táchira, black cherts occur. Megascopic fossils (with the exception of fish scales in some areas) are rarely encountered, except in concretions where *Didymotis trinidadensis?*[26] (like a small *Inoceramus*), various ammonites and groups of small forms (of the order of 0.5 centimeter) believed to be brachiopods,[27] are characteristic.

This formation is black only on freshly cut river sections, where most of its study has taken place; elsewhere it usually weathers by fading through chocolate and tan to a very light color, in which condition it has been confused with the overlying Eocene by reconnaissance workers. This fading is well seen in the south mountain front of eastern Venezuela (where approximately 6,000 feet of the formation may be measured), as well as in the Canaguá area west of Mucuchachí. In such places the same horizon can be traced from its black color in the river to its light phase on the peaks.

As the fading and leaching progresses, more soluble constituents are removed and the rock becomes notably lighter in weight as well as in color. This porous light-colored rock may appear to be mainly composed of radiolarian or diatom remains, and even approach tripoli in general appearance. The light rock used as building stone in Santa Barbara seems to be an extreme case of this leaching, but as the writer has not visited the quarry nor seen definite fossils in the rock, he is not prepared to do more than suggest that it may be Cretaceous. This rock has been referred to by some observers as "diatomaceous earth."

This part of the Cretaceous, the most widespread formational unit in northern South America, occupies large areas of the northeast plunging end of the Venezuelan Andes, where it gives way to the Coast Ranges, and its distribution in that region was mapped by Liddle.[28] Farther southwest, on the southeast mountain front in Zamora, it is generally found below the Eocene except where faulting obscures relations. Jones and Whitehead[29] mention the prominent occurrence on the main transmontane trail northwest from Barinas (Fig. 3).

[26] G. A. Waring, "Geology of Trinidad," *Johns Hopkins Studies in Geology No. 7* (1926).

[27] J. A. Tong, oral communication.

[28] R. A. Liddle, *op. cit.*

[29] W. F. Jones and W. L. Whitehead, *op. cit.*

In the region of the River Quiu and Santa Barbara, already mentioned, the dark shales above the Cogollo limestone ledges are thin (less than 300 meters) and not fossiliferous, and in the River Quiu they contain asphalt-soaked sandstones and beds of grahamite. The contact with Tertiary beds is not clean-cut, but there is no discordance in dip and strike here or elsewhere in the area between Lower Tertiary and Cretaceous.

In the western Táchira region the formation is well developed, with the typical concretions, bands of black chert, and interbedded Cogollo limestone near the base.

On the northwest mountain front, also, the formation is everywhere present except where faulting is a prominent feature, as northeast of the Onia fault area.

Since this is the first published mention of the Cretaceous in the Santa Barbara region of the southeast mountain front, some further details as to the basis for this mapping may be called for. Ten kilometers west of Santa Barbara on low hills near the River Suripá, close to the metamorphic contact, there are marls containing fragments of ammonites and other fossils. On the northeast of Santa Barbara are the outcrops of Cogollo limestone character described in the preceding section. In the intervening area the rivers are too small to furnish many useful outcrops of the entire section. The River Santa Barbara is not too small, but it has become an aggrading stream by the time it reaches the sedimentary rocks, and only two outcrops of sandstone are found overlying the gneissoid rocks of the metamorphics. These resistant sandstones are probably equivalent to the sandstones mentioned as of Barranquin age on the rivers Pedraza La Vieja and Quiu, and the higher Cretaceous shales (and limestones if present) have been eroded below the present level of gravel and boulders. As mentioned previously, the limestones of the River Quiu only barely protrude above the river gravels.

The outcrops on the River Caparo (Figs. 3 and 4), both on the road to Mucuchachí from Santa Barbara and farther southwest near San Antonio de Caparo, are less convincing because not coupled with fossil evidence, but the lithologic character is so similar to that of the known Cretaceous at relatively short distances (north to Canaguá and Pregonero, east and southeast to Santa Barbara), and so different from that of the Tertiary at the same points, and the relations of other formations are so compatible with this interpretation, that the writer has no hesitation in mapping thus at the present stage of knowledge of the region.

CENOZOIC

The rocks of this age on the northwest mountain front of the Venezuelan Andes as well as in many other areas have been extensively treated by Liddle, and some information on these rocks in the Venezuelan Andes interior was contained in Jones and Whitehead's contribution.[30] Only a summary treatment is attempted here.

The almost universally clastic Tertiary rocks are rarely fossiliferous, and subdivisions have been based on lithologic character and color.

In general the Eocene is more fossiliferous, in places, than the younger rocks, but fossils are rare. The Toas limestone,[31] with its diagnostic *Venericardia planicosta* and abundantly fossiliferous strata, is rare and discontinuous even in northern Maracaibo basin, and has never been reported in the Venezuelan Andes. The Misoa-Trujillo sandstone of Liddle is generally recognized by its hard sandstones and lignite seams, but these, of course, are not everywhere conspicuous and beds occupying this position are commonly shaly and different from younger Tertiary rocks only in darker color, more even grain, and greater compactness.

In eastern Venezuela there is little if anything on a megascopic basis to distinguish the Eocene sandstones from those of the basal Cretaceous except their position with respect to the La Luna formation and Cogollo limestone. A similar confusion of the Eocene with the Cretaceous sandstone is easily possible in the Táchira region of southwestern Venezuelan Andes for the reconnaissance observer, whenever the intervening marine Cretaceous beds are not recognized.

LOWER TERTIARY

On the northwest mountain front of the Venezuelan Andes, numerous subdivisions of the Tertiary have been made on the basis of color and lithologic character, but these are naturally not persistent over long distances. Practically no megascopic fossils are found, and microscopic forms are rare in the Eocene and generally lacking in the younger rocks. A little work on heavy minerals on the southeast mountain front had not been very fruitful in 1931.

On the southeast mountain front the general usage was to call the lower sandstones and shales "Eocene." Erratic folding usually present in the broad belt of these rocks in the Pedraza-Barinas sector makes the measurement of a continuous section difficult, but 1,000 meters can be measured northwest of Pedraza and the base is not exposed.

[30] W. F. Jones and W. L. Whitehead, *op. cit.*

[31] R. A. Liddle, *op. cit.*

A series of mottled clastics, with a thickness of 3,000 meters or more at the mountain front where they are exposed, was called by the writer the "silt-conglomerate" beds.[32] Near Barinas these beds can be subdivided into "Red" below and "Black" above, after the dominant color in mottling, but these color changes are uncertain and probably do not persist throughout long distances (Fig. 3, *Tm*, *Tom*).

All these beds have been involved in folding, the folds being nearly vertical in places, but it is probable that folding was progressive during "silt-conglomerate" time. A series similar in lithologic character and degree of folding west of Maracaibo was tentatively assigned by the writer to the Oligocene-Lower Miocene, and such a classification is convenient here, thus including all sediments up to the late phases of the Andean revolution.

UPPER TERTIARY (POST-MIDDLE MIOCENE)

In the Maracaibo basin it is known from drilling, and from some outcrops in the northern part, that poorly consolidated "mottled clays" occur to a thickness of 5,000 feet and more. These show no sign of being involved in compression folding, as do the otherwise somewhat similar Oligocene-Lower Miocene strata mentioned in the preceding paragraph. There is evidence (west of Maracaibo) that movement during and since the deposition of these beds has been confined to foundering by irregular faults of portions of the Maracaibo basin, movements representing releases of tension and readjustment, isostatic and otherwise, stored up during the violent compressive stresses of the Andean revolution, and not following the Andean tectonic lines closely.

On the southeast side of the Venezuelan Andes nothing is known of these sediments (except that they probably exist under the llanos alluvium of the Orinoco basin), unless some of the upper part of the "silt-conglomerate," which everywhere shows low dips basinward in the Barinas sector, might be considered of this group.

STRUCTURE

The "Baúl Hinge zone" (Fig. 1) is an area of anomalous structure which has influenced sedimentation since the early part of Tertiary time. Within this area the west-east to east-southeast trend of the Coast Ranges has contended with the northeast strike of the Vene-

[32] On the northwest mountain front the equivalent of this "Eocene" and the lower part of the "silt-conglomerate" have been split into a number of formations. Most of the "silt-conglomerate," however, seems to be exactly equivalent to the Agua Fria conglomerates across the mountains, where a similar thickness is exposed and involved in commensurate folding.

zuelan Andes and with the north-northeast to north-south trend of the Sierra Oriental of Colombia, resulting in isolated structural phenomena only a few of which have been mentioned in the literature. Erratic strikes contrast with the comparative simplicity of strikes in the adjoining mountain areas, and the Tertiary has a development distinct from that in adjacent areas. This "zone" takes its name from the unique Baúl Hills, a few igneous and metamorphic hills protruding from the llanos alluvium about halfway between the Coast Ranges and the Brazilian shield (Fig. 1).

The striking straightness of sections of the mountain front, both on the northwest and southeast flanks of the Venezuelan Andes, has led many to ascribe a major role to faulting in definition of the mountain form. Faulting parallel with the trend of the mountains does occur, but such faults which can actually be determined are invariably at or near the boundary between sediments and igneous or metamorphic rocks, miles, in places many miles, distant from the frontal hills on the straight-line arrangement of which faulting might be postulated. The areas of very straight lines outlining the frontal hills have all been mapped in detail, and it is certain that any faulting which may influence their position is so deep-seated (Fig. 4) that its effect upon them can only be considered speculatively. Study of seismograph records with a computed range vertically of 15,000 feet has failed to show any signs of such faulting at three points, including Santa Barbara, on the southeast mountain front.

On the other hand, these segments of straight mountain front are defined by offsets of varying size, due to diagonal faulting striking usually about north-south. The most conspicuous of these is the Onia fault,[33] which appears to extend completely across the mountains and passes near San Antonio de Caparo (Figs. 3 and 4). Next in size is that at Socopó River southwest of Pedraza (Zamora), which divides two quite distinct sectors of the southeast mountain front (Fig. 3). Others less obvious and smaller appear as evident boundaries between other structural phases of the mountain front.

The faults which Peter Christ[34] postulates at the contact of "Tertiary" and metamorphic rocks, in his cross sections showing his interpretation of geologic history of the Mucuchachí area, have no basis in fact, as cross sections (Fig. 4) show.

The only large, relatively gentle, fold mapped is in the mountains proper between Pregonero and San Antonio de Caparo, called by the

[33] Position indicated on Plate 3, R. A. Liddle, "Tectonics of Maracaibo Basin, Venezuela," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11, No. 2 (February, 1927), p. 177.

[34] P. Christ, *op. cit.*

writer "Colorado anticlinorium." A broad area of Red-beds is exposed on this arch and there is reason to believe that it plunges southwestward toward the south mountain front, south of San Cristóbal de Táchira. Northeastward it apparently runs into the Onia cross fault.

West of the Colorado anticlinorium, in western Táchira, folding is also relatively moderate and several anticlines exposing Barranquin sandstone (*Kl*, Fig. 3) are found. One small anticline exposing a small patch of La Luna ("Colon shales"?) rimmed by Eocene, near Alquitrano, has the distinction of being the first oil field in Venezuela, having been exploited for a few barrels since the early 1880's.

The outcrop of sediments on the northwest mountain front, is in structure a simple steep dip into the Maracaibo basin, decreasing in the younger Tertiary clastics. This holds for the western part, up to the Onia fault near the state boundary of Táchira and Mérida, beyond which the structure is more complex, but without reversals until the Motatan-Valera vicinity is reached. Here, in a broad belt of Middle Tertiary (Oligocene-Lower Miocene?), there is an anticline which has been drilled to about 6,000 feet without penetrating the thick Tertiary beds.

Across the mountains from the point last mentioned, between Barinas and Barinitas, there is a small wrinkle in the "silt-conglomerates," also drilled to about the same depth with the same negative results. The belt of Eocene in this area is locally wide, but is rather highly folded with no persistent large folds. Farther southwest, northwest of Pedraza, there is a small anticline exposing the Eocene, with dips up to vertical on both flanks. From the Socopó fault west of Pedraza, to San Antonio de Caparo (Fig. 3), there is a steep dip, ranging to vertical or slightly underturned, into the Orinoco basin, uninterrupted within the narrow belt of Cretaceous and Tertiary sediments.

Oil Possibilities

Seepages of oil are abundant along the outcrop of Cretaceous, especially in the La Luna formation, in the Venezuelan Andes. Where seepages are found in the Tertiary rocks they are generally deep in the Eocene section, supposedly or certainly near the Cretaceous. Several exceptions to this rule occur on the northwest mountain front, but diagonal faulting may afford egress to the oil from deep Cretaceous sources. On the other hand, at several places in the Maracaibo basin there is evidence that oil originates within the Tertiary, and such a possibility is not excluded for the Venezuelan Andes.

The only seepage distant from the Cretaceous outcrop is east of

Mucutuy in the state of Mérida, northeast of Mucuchachí and at an elevation of nearly 10,000 feet, in shales below the Red-bed conglomerates which may be of Carboniferous age. This suggests possibilities for oil in structures exposing the Lower Cretaceous or Red-beds, of which many exist in the southwestern part of the Andes.

The structure northwest of Pedraza, which has a seepage on its crest near the eastern, probably faulted, end, may be productive, but the possibly productive area is small on account of the steep dips, and transport problems resemble more those of the mountain interior than those of the previously tested parts of the mountain fronts.

The Alquitrano oil field, on the small structure mentioned in the preceding section, was still producing a few barrels daily by hand pumps in 1930. This was refined at the field and sold locally in Táchira.

In summary, with the present development of the local market, only large production cheaply obtained is practicable at present. The mountain fronts are ruled out for large production because where dips are not too steep, structure is either too erratic (wide Eocene belts), or the Middle Tertiary cover is too thick. The southwestern part of the Venezuelan Andes is not condemned and has features which appear favorable, but problems of transport are unsolved, and even preliminary studies of a commercial character must await major changes in the world petroleum outlook.

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SAFETY OF WATER-FLOODING PRESSURES AT BRADFORD, PENNSYLVANIA[1]

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ABSTRACT

The properties involved in the problem reviewed are located in the Bradford field, McKean County, Pennsylvania. A large number of wells were abandoned during early years of development, but operations have been revived by the Petroleum Reclamation Company, which is reclaiming the field by the water-flooding process. The system used is locally known as the "five-spot" process, by means of which water under abnormal pressure is forced down intake wells at all corners of a square and the crude is recovered in due course from an oil well at the center. Since the entire production area is covered with a pattern of such wells, it is evident that the "pay" zones in the Bradford sand become saturated with water at increasingly high abnormal pressures varying in accordance with the intake pressures.

The question placed before the writer in the summer of 1932 was whether any danger might ensue from loss of oil or destruction of strata or properties owing to excessive pressures transmitted against the roof of the sand by means of intake flooding. Some of the criteria considered were earthquakes, gas and volcanic blow-outs, surface subsidence, salt-dome mechanics, hydrostatic conditions in known aquifers, formulas for the strength of materials, etc. The answer at that time, after approaching the problem in various ways, was that no danger would result up to an intake pressure of about 3,000 pounds per square inch and probably much higher. Although time is not available to bring the researches thoroughly up to date or to carry any research to its ultimate conclusion, the results of the original work are here given for such interest as they may hold for a petroleum geologist. It is hoped the several branches of study will be carried forward by other persons.

ADVANCE SUMMARY

A problem placed before the writer in the summer of 1932 was to determine the extent to which artificial intake pressures may safely be raised in the water-flooding method of reclaiming abandoned oil fields, with special reference to properties of the Petroleum Reclamation Company in the Bradford field of northern Pennsylvania. The study was based on both experience and theory, anticipating experimentation that has since been carried on by the company. The writer is informed that nothing that has subsequently taken place in the field need cause any departure from the conclusions given. After

[1] Manuscript received, February 25, 1935. This study was made possible owing to the wise foresight of the Petroleum Reclamation Company of Bradford, Pennsylvania, by whom the researches were fully financed. Owing to lack of time on the part of the writer, the report has not been brought up to date and is only modified in such main respects as are necessary for purposes of publication. It is presented to The American Association of Petroleum Geologists with the permission of the Petroleum Reclamation Company. The writer wishes to acknowledge his indebtedness to the management of that company for the coöperation that prompted this wise attitude.

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prosecuting the researches in various directions, checking one method against another, the following tentative results were obtained.

1. Intake pressures above approximately 1,400 pounds apparently can not be used without taking the precaution to plug, fill, and render impervious all abandoned wells, most of which are many years old. This may be accomplished through use of concrete; or, after attaining higher reservoir pressures, recourse to hot asphalt may be necessary, since this substance is successfully used by engineers in grouting around dams.

2. According to theory and the formula for strength of materials, the application of intake pressures of approximately 3,000 pounds per square inch appears safe after all old wells have been successfully closed.

3. Intake pressures higher than approximately 4,500 pounds per square inch do not appear reasonable after careful study of the various factors, and they seem to be progressively of doubtful safety according as the pressure rises above 3,000 pounds. Nevertheless, any danger from a few hundred pounds excess pressure is of such speculative nature that a fair assumption is (after finally closing old wells) that some increase over the theoretical mathematically safe figure may be justified.

4. It seemed probable that, if effect on the "cap rock" of the sand and the directly superposed beds be the one factor injurious to the field and problem, the harm might already have been done. It did not appear probable that water or oil had penetrated far above the sand except along channels furnished by old wells, but the possibility must be recognized that water or oil may have thereby entered the shallow sands, ascended, and moved some distance laterally. It is improbable that pressures of less than 3,000 pounds per square inch could result in disastrous phenomena except where water and oil escape from the sand by means of old wells.

5. No surface bulging, heaving, or rupture (unless in and close to old wells) is to be expected. The phenomena exhibited when an unsafe pressure is attained are more likely to be a breaking down of the near-roof over the sand, causing outbursts of water through or along wells that were believed to have been thoroughly closed, muddying or "sanding up" of oil wells, et cetera. Effects from an excessive internal pressure are more likely to be invisible than visible.

6. As a general summary, the project of moderate pressure increase was considered a safe one, subject to careful study by the company's engineers at every step in the process. No ultimate maximum pressure that may be decided on in advance can be definitely

promised; but the policy of pressure increase is capable of instant modification whenever field manifestations render this desirable.

7. The present study pertains particularly to properties of the Petroleum Reclamation Company, which, for convenience, are considered as one mile wide. If it happen that adjoining properties be later flooded to a marked extent, the outlook might be modified, not in a qualitative but in a quantitative way.

Plan of report.—Having given a brief resumé of the results of the investigation, the writer proceeded to take up step by step the various criteria which might be expected to furnish evidence on the problem in hand. The Bradford situation was first reviewed, followed by an inquiry into evidences derived from use of explosives, those given by earthquakes, those connected with the mechanics of salt-dome formation and then with blow-out wells. The intent was to show that, in so far as such lines of investigation give any evidence at all, this is (even if not definitely helpful) not opposed to the safety of the project. Then ensues a discussion of actual conditions prevailing in oil and gas and water sands with which the writer is familiar to show that the Bradford field is, so far as determinable, the only one in the world where there has been to date a net excess of reservoir pressure (either natural or artificial) over weight of rock column. Numerous examples of mine caving are cited, in order to draw any possible inferences from correlation of the pheomena exhibited. In this case it was shown that nothing exactly parallel or converse to Bradford conditions has come to light, but nevertheless that a company does not need to be alarmed on account of subsidences in general. Finally, having canvassed the field of phenomena with any possible bearing and having found nothing opposed to the safety of the project (even though various factors seemed from time to time to prejudice it), the mechanics of materials was brought in to prove mathematically how the rock column overlying the Bradford sand may reasonably be expected to sustain a pressure of at least 3,000 and possibly over 4,500 pounds per square inch. We naturally recognize the fact that earth structure can not be submitted to laboratory tests like a bridge or an automobile and that consequently defects in any of the rocks may exist—unknown and indeterminable from the surface—that may call a halt during the proposed flooding.

The word "sand," where used in this report, should be understood as being the common oil-field designation for "sandstone."

EVIDENCE DERIVED FROM BRADFORD EXPERIENCE

Preliminary statement.—Since this paper is not intended to go into the history or geology of the Bradford field, the reader is referred to

descriptions of the field and to the general practice of water-flooding as published in articles too numerous to be itemized here. A fair discussion of the system at the approximate time when the study was made will be found in an article by Fettke.[3] The principal lessons to be derived from experience with Bradford flooding are (a) that flooding has proved highly successful and that, up to a certain approximate pressure, it has caused no harmful effect, but that (b) above that pressure considerable amounts of oil and water escaped in the past from old abandoned wells until these had been plugged and tightly sealed. The Petroleum Reclamation Company was remarkably sucessful in sealing such wells.

Some incidents of water-flooding.—At the time this investigation was conducted, Bradford experience covered the use of artificial intake pressures up to about 1,900 pounds per square inch, additional to the weight of the column of water. This 1,900 pounds was only applied in a single instance, in which the well pipe soon showed pin-holes. Otherwise the intake pressures had not exceeded 1,600 pounds per square inch and were as a rule limited to less than 1,300 pounds per square inch. This approximate understanding gives the perspective from which to approach the problem of pressure increases.

Several incidents of flooding experience may be worth comment. Two days after the intake pressure was raised to about 1,600 pounds per square inch—which was 200 pounds more pressure than had been previously applied—and three or four days after an unusual rain, oil, amounting to a barrel or more per day, began to emerge from a formerly good spring of drinking water in a deep valley on the east side of the field. Any instance of this sort, if reported in future, may indicate (a) the presence of some unknown unplugged well in the vicinity or (b) the possibility that some of the old wells were inadequately plugged, so that fluid from Bradford sand is enabled to rise along the channel of the old hole and emerge through a near-surface sand bed. Since the company has actually plugged more than 200 old wells and since records of their positions were not originally kept, it seems possible that a few others may have been missed.

Presence of other sands.—Contrary to a common outside assumption, several "sands" occur in the section between the Bradford sand and the surface. A study of the log of the Petroleum Reclamation Company's well No. K-17 on the Looker tract, the surface elevation of which is 2,128 feet, showed about 11 per cent of sandstone (not including beds of "sand and shale"), the balance of the section being

[3] C. R. Fettke, "Recent Developments in Flooding Practice in the Bradford and Richburg Oil Fields," *Tech. Pub. 328, Am. Inst. Min. Met. Eng.* (1930), 30 pp.

shale with exception of thin limestone "shell" directly above the Bradford sand and reports of "shell" (perhaps in part limestone) elsewhere in the log. It is evident, therefore, that plenty of sandy beds are present in the section, so that oil and water might migrate into them under pressure if open channels exist along joint cracks, faults, or old wells. The fact that water has not emerged at a great number of localities throughout the field is a fair sign that open faults and joint cracks do *not* exist. Local geologists tell us that the field has no faults.

For the most part the sand beds are reported only 5–40 feet thick; but several of them, commonly recognized by geologists, would easily hold water or oil under pressure. The "First sand" is part of a horizon of sandy, calcareous shale and is variable in character. In limited areas in the southwest part of the field it consists of clean sand grains, but elsewhere it carries much calcareous and argillaceous material. Its position is 1,000–1,200 feet above sea-level.

The Chipmunk sand—800–1,000 feet above sea-level where present—is more uniformly of good character than either the "First sand" or the "Second sand."

> Throughout the northwest part of the field it is a medium-grained, brown, medium-soft to hard sand ranging from 20 to 50 feet in thickness. Throughout the central and east sections it is reported as ranging from 10 to 25 feet in thickness, but is composed largely of thin alternating layers of shale and fine sand.

The Chipmunk pool, in which the sand of that name is the important producing horizon, lies between Limestone and Vandalia in Cattaraugus County, New York, beyond the limits of the Bradford pool but continuous with it. The Chipmunk sand ranked next to the Bradford as a lucrative producer of oil. Unlike the Bradford, however, production from it was flashy and its productive area is limited to a few thousand acres in the northwest part of the field. Some wells produced as much as 250 barrels per day initially.

The "Second sand," 600–900 feet above sea-level, is more irregular than the "First sand" but is otherwise similar in character and extent. In several thousand acres in the western part of the field it is a tightly cemented, hard, light brown, fine-grained sand; elsewhere it is very hard and calcareous, in many places the

> hardest stratum encountered in drilling to the Bradford sand. Many fishing jobs in drilling and difficulties in running packers are the outcome of a tight place in the hole at this horizon.

Furthermore, not only are these sands present in the Bradford area, but they have in the past held oil and presumably they retain

some original oil at the present time. The "First sand" was rarely productive, but the "Second sand" produced oil in commercial amounts on the west edge of the pool—southwest, west and for a short distance north of the town of Bradford. In the West Branch area, west of Bradford, within recent years wells have been completed with an initial production of 25 barrels a day from the "Second sand," according to Newby, Torrey, Fettke, and Panyity in 1929.

Sealing old wells as prerequisite to successfully raising pressures.—The experience with escape of some water and oil by way of old wells and shallow sands, although apparently unimportant and temporary, indicated that no considerably higher pressures should be expected without adequately closing the old wells.

This is a prerequisite to successful flooding at high intake pressures. If concrete filling does not prove effective in any case, the use of hot asphalt under pressure, as in grouting around dams, was recommended. The method and equipment in use, covered by a presumably valid patent, are described by George W. Christians,[4] Chattanooga, Tennessee, as applied to actual stoppage of leakage channels by filling with asphalt forced down a pipe and kept hot by an electrical current until it reaches its position in the rock.

Evidence from other fields.—In order to determine whether any pressure lesson could be gained from experience in other fields, a search was made for results. One large company was directly questioned and, in addition, the literature was consulted in regard to early efforts of flooding at Pithole, Pennsylvania,[5] Oil Springs in Lambton County, Ontario,[6] and in Kern River field of California.[7] No instance could be found of a pressure as great as that in constant use at Bradford.

An effort was also made to ascertain what pressures have been attained by using gas and air for reclaiming oil fields. According to Lewis,[8] pressures used in the Marietta process range from 30 to a maximum of 320 pounds per square inch. The writer is informed by the Alberta Gas Conservation Board[9] that gas from the Turner Valley field of Canada

[4] "Asphalt Grouting under Hales Bar Dam," *Eng. News-Record*, Vol. 96, No. 20 (May 20, 1926), pp. 798–802.

[5] J. F. Carll, "The Geology of the Oil Regions of Warren, Venango, Clarion, and Butler Counties," *Second Geol. Survey of Pennsylvania*, Vol. 3 (1880), pp. 256–89.

[6] L. G. Huntley, "Probable Causes of the Decline of Oil Wells and Suggested Methods of Prolonging Yield," *U. S. Bur. Mines Tech. Paper 51* (1913), pp. 9–21.

[7] J. O. Lewis, "Methods for Increasing the Recovery from Oil Fields," *U. S. Bur. Mines Bull. 148* (1917), p. 1078.

[8] *Ibid.*, p. 52.

[9] Personal letter from F. P. Fisher, dated June 22, 1932.

is being used in re-pressuring of the old Bow Island field, about 130 miles southwest, through the existing pipe line. This is being done on the assumption that the maximum safe pressure of storage in that field will be approximately the original rock pressure of the field, or about 100 pounds. As far as I know this basis has been used as the limit for re-pressuring operations in a number of gas storage projects.

EVIDENCE FROM USE OF EXPLOSIVES

In commencing the study it was supposed that some idea of what pressure the overlying strata would sustain might be gained by consulting nitroglycerine companies, whose research departments could conceivably have information on the subject. Courteous replies to letters to the American Glycerine Company were received[10] but the writers conceded that they *do not know* the pressure developed by the explosion of a charge of explosives.

A few years ago the du Pont Company attempted, in their laboratory, to secure an answer to this question and they did obtain what they thought was an approximate answer, which was obtained by interpolating some actual laboratory results. They concluded that twenty percent straight nitroglycerine dynamite, which is a rather low grade explosive, would develop a pressure of something like 400,000 pounds per square inch. Pressure results from shooting a charge of liquid nitroglycerine are, from the nature of things, impossible to obtain. Theoretically, if nitroglycerine is exploded under the above condition, practically an infinite pressure would be developed, since if complete explosion is obtained, the normal resulting gases could not be compressed to the original volume of the nitroglycerine, by anything short of infinite pressure; at least the compression curves of the resulting gases would indicate the above conclusion.

Efforts to ascertain over what horizontal area the force of an explosion would result were without avail. The American Glycerine Company writes:

> We have no way of knowing over what horizontal area the pressure from an explosion will be exerted.
>
> A good many factors will no doubt influence any answer that could be given to this question.

On the contrary, inquiry from the United States Bureau of Mines resulted[11] in the statement that

> Numerous observations in mines, where the workings have broken into drill holes that have been fired, show that the visible effects of the shots are limited and die out rapidly from the point of the blast.

[10] Personal letter dated May 27, 1932.

[11] Personal letter dated June 16, 1932.

The writer of that letter, referring to discussion by J. A. Garcia[12] of a paper by Young, and mentioning coal-mining blasting, concedes that, judging from resulting litigation, it appears that a considerable amount of damage was done in a vertical direction.

It is admitted by Hill[13] that data on the size of cavities resulting from the use of high explosives are meager. A review by him of a paper by Rison[14] was accompanied by the loan of some photographs exposing holes that had been "shot" in a limestone quarry about 12 miles north of San Antonio, Texas, in which the effects of the explosions were visible only a few inches from the holes.

The heat and kinetic energy generated by well shooting have also been discussed by Paul F. Lewis,[15] in a paper that has not been perused. There appeared to be no probability that further study of the effect of explosives would be helpful in a solution of the problem.

EVIDENCE FROM EARTHQUAKES

Efforts to learn what pressures had been exerted by great earthquakes were in general unsuccessful, for, in the nature of the problem, such figures are difficult to obtain. The writer consulted a report on the San Francisco earthquake,[16] which gives the following information:

> We can also determine the work done at the time of the rupture; it is given by the product of the force per unit area of the fault-plane multiplied by the area of the plane and by half the slip. If we take the depth of the fault at 20 km. (12.5 miles), the length at 435 km. (270 miles), the average shift at 4 meters (13 feet), and the force at 1×10^8 dynes* per square centimeter (1,450 pounds per square inch), we find for the work 1.75×10^{24} ergs (1.3×10^{17} foot-pounds), or 130,000,000,000,000,000 foot-pounds. This energy was stored up in the rock as potential energy of elastic strain immediately before the rupture; when the rupture occurred, it was transformed into the kinetic energy of the moving mass, into heat and into energy of vibrations; the first was soon changed into the other two. When we consider the enormous amount of potential energy suddenly set free, we are not surprised that, in spite of the large quantity of heat which must have been developed on the fault-plane, an amount was transformed into elastic vibrations large enough

* The dyne is the force which, if applied to the standard gram body, would give that body an acceleration of 1 cm. per sec.^{2}; that is 1 dyne = 1/980,665 of a gram force.

[12] C. M. Young, "Subsidence Around an Oil Well," *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 74 (1926), p. 810.

[13] Personal letter from Bureau of Mines, June 16, 1932.

[14] C. O. Rison, "Manufacture of Nitroglycerine and Use of High Explosives in Oil and Gas Wells," *Trans. Amer. Inst. Min. Met. Eng., Petroleum Development and Technology, 1928–29* (1929), pp. 240–312.

[15] Read before the Petroleum Safety Council at Tulsa, Oklahoma, September, 1931.

[16] Harry Fielding Reid, "The Mechanics of the Earthquake," *Report of the State Earthquake Investigation Commission*, Vol. 2, p. 22.

to accomplish the great damage resulting from the earthquake and to shake the whole world so that seismographs, almost at the antipodes, recorded the shock.

In the case of an earthquake the force is generally a strain.[17] Reid[18] tells us that the force necessary to produce extended distortion at the fault a short distance below the surface is 1,930 pounds per square inch. Tests made at the Watertown Arsenal[19] gave values between 1,700 and 2,900 pounds per square inch for the strength of granite under strain.

In the case of the San Francisco and other earthquakes, it must be borne in mind that the comparatively small force in pounds per square inch is not what caused the damage; but the vast aggregate of such force originating at tremendous depths in the earth and spread out over many miles has caused an elastic strain that ruptured the rocks.

The reader will please note that Reid does not find, on mathematical calculation, that the force that originated the earthquake was 1,450 pounds per square inch, but he evidently uses this figure as being considered "the ultimate shearing strength of granite." We need not assume, therefore, that there is any evidence, derived from earthquake experience, that the force which produced the San Francisco earthquake was *only* 1,450 pounds per square inch.

A communication from the secretary of the Seismological Society of America[20] informs us that

> we have no knowledge of the stresses which are exerted along great earthquake faults from any measurements made in the field. In 1905 there was displacement along the San Andreas Fault of 21 feet in the neighborhood of Olema. In the report of the State Earthquake Investigation Committee Harry Fielding Reid surmised from various sparse data of surveys that there was no permanent displacement at the time of the earthquake at points at a distance of more than about five miles on either side of the Fault. However, the data for such a statement was extremely scant. If such were the case, we would have a certain measurement of the stress which the rocks could accommodate. As it is, however, we can say nothing.

[17] The theory of elasticity uses the word *strain* to signify an elastic change of shape or of value caused by external forces; whereas *stress* is a resisting force which the body opposes to a strain, and with which it tends to diminish it.

[18] Harry Fielding Reid, *The California Earthquake of April, 8, 1916*, Vol. 2 (1910), 191 pp. (p. 21).

[19] U. S. Arsenal at Watertown, Massachusetts, *Report of the Tests of Metals and Other Materials for Industrial Purposes Made with the United States Testing Machine at Watertown Arsenal, Massachusetts, during the Fiscal Years Ending June 30th, 1890, 1894 and 1895* (Washington, D. C., 1891, 1895, and 1896).

[20] Perry Byerly, in a personal letter dated June 13, 1932.

EVIDENCE FROM SALT-DOME MECHANICS

Preliminary statement.—It seemed possible that some enlightenment might be furnished by the mechanics of concentration of rock salt, rising against tremendous overlying pressure in oil fields of the Gulf Coastal Plain of Texas and in Mexico, Louisiana, Germany, Roumania, Persia, Arabia, and elsewhere. A search was made of the writer's own records and salt-dome literature[21] in hope of finding something helpful on this subject.

Salt domes of Texas and Louisiana.—The salt domes of the Gulf Coast are well known, since many oil fields and the largest sulphur mines in the world are situated upon them. Although the question of the origin of these structures has led to a vast aggregation of literature, there is still no general acceptance of the genetics in all details. One fact, not generally accepted, is well put by Barton.[22]

> In the light of present knowledge it seems futile to predicate the origin of the American salt domes by any other method than by upward intrusion consequent upon, and coincident with, plastic yielding to deformation by a preexisting salt mass, in all probability an originally flat-lying sedimentary salt bed.

Nearly all students of the coastal plain of Texas are of the opinion that the salt, in this geologic province at least, occurs at the intersections of fault lines or underlying geologic axes.

Plasticity of salt.—Harrison[23] emphasizes the fact—noted by many salt-dome investigators—that

> One outstanding characteristic of the mixture of salt, gypsum and clay which makes up the bulk of the salt dome material is its plasticity. It seems to be capable of flowing in somewhat the same manner as glacial ice.

It is now generally recognized that the flowage of salt from horizontal strata into domes is due to being pressed as a very plastic

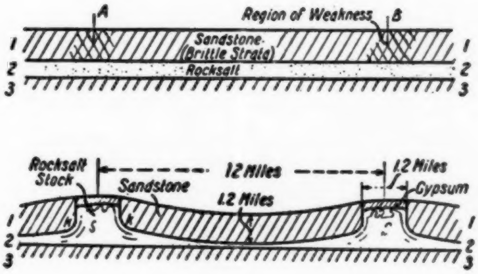
[21] Although there is a vast array of literature on the subject of salt domes, the most complete accounts are to be found in the following publications.

Geology of Salt Domes Oil Fields, a symposium on the origin, structure, and general geology of salt domes, with special reference to oil production and treating chiefly the salt domes of North America (containing articles by DeGolyer, van der Gracht, Stille, Barton, Powers, Suman, Deussen, and others), published by *Amer. Assoc. Petrol. Geol.* (1926), 797 pp.

"Symposum on Salt Domes" (containing articles on Germany by James Romanes; on deformational problems by G. M. Lees; on Texas and Louisiana by F. G. Clapp; on Persia by J. V. Harrison; on Arabia by Arthur Wade; on theory and origin by DeGolyer and Launcelot Owen; on salt-dome geochemistry by Murray Stuart), *Jour. Inst. Petrol. Tech.*, Vol. 17 (1931), pp. 251–383.

[22] Donald C. Barton, "The American Salt Dome Problem in the Light of the Roumanian and German Salt Domes," in *Geology of Salt Dome Oil Fields*, Amer. Assoc. Petrol. Geol. (1926), pp. 167–208; pp. 202–04.

[23] J. V. Harrison, "Salt Domes in Persia," *Jour. Inst. Petrol. Tech.*, Vol. 17 (1931), pp. 300–20 (p. 316).



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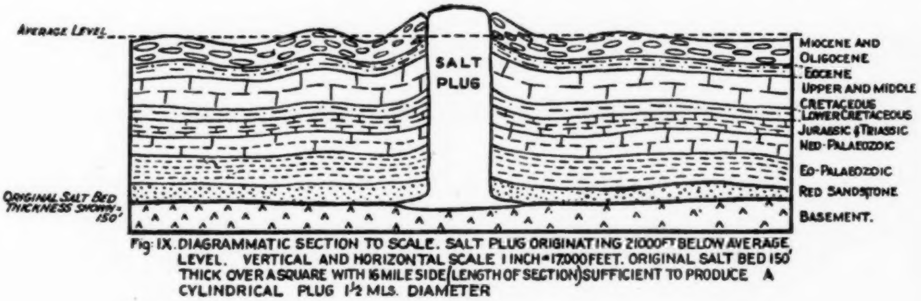

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PLATE I.—Diagrams to illustrate formation of salt domes due to pressure of overlying strata.

A. Two stages in salt-dome formation (after Nadái and Wahl, in *Plasticity*, p. 320).

B. Salt dome situated in unconsolidated strata (after J. V. Harrison, *Trans. Inst. Petrol. Tech.*, Vol. 17, 1931, p. 308).

material between rigid parallel layers, enabling the salt to move laterally and ascend through vertical fissures at some point of slightly reduced pressure.

We are reminded by Nadái and Wahl[24] that

> Cases where a layer of very plastic material is pressed between two rigid parallel layers and as a consequence of the lateral pressure flows out to the sides or ascends through vertical fissures can be observed in nature on a large scale. Landslides on the mountain slopes in the neighborhood of lake shores arise because of the high plasticity of a clay layer enclosed between rigid layers. . . .
>
> A further important example found in nature is shown by the rock-salt stocks or domes occurring in the North German plains and in the Mexican Gulf regions. . . .
>
> Initially the rock salt lies in a layer of approximately constant thickness between rigid strata, just as it was precipitated from the ocean by the slow drying of restricted portions of the sea during the Perm period and covered subsequently by other sedimentary rocks. Rock salt has a specific gravity of 2.15 to 2.17. The specific gravity of the overlying beds may depend on their composition and may also increase with increasing depth below the earth surface. As the average density of the more compact rocks is about 2.4 to 2.6, it seems not unreasonable to assume that the overlying rigid strata in general are denser than rock salt. It will be sufficient to assume that the upper strata, lying above the rock-salt layer at certain points . . . have a slightly smaller density than at other points. Below these regions the pressure in the rock-salt layer, due to the weight of the overlying strata, will be slightly smaller than in the surrounding points of this layer. Hence there will exist a small pressure difference in all radial directions meeting below the points such as A or B as centers. As rock salt is a highly plastic material, comparatively small differences of pressure will be sufficient to produce movement and plastic flow within the rock-salt layer. Due to the high degree of plasticity of the material in this layer, the salt will tend to flow radially inward towards the centers of lowest pressure . . . and will gradually accumulate there more and more, at the same time also bending and lifting up the overlying layer of the crust. Evidently this tendency for accumulation of the lighter subcrustal material will last only until the slightly disturbed isostatic equilibrium around the centers of flow has again been restored. . . .
>
> As has been pointed out by Lilley, certain phenomena, as for example the regular orientation of the long axes of the domes with oval horizontal cross-section in North Germany (and the clear relation of these latter to the directions of the folding movements in the neighboring old mountain ranges), indicate that mountain folding and orogenic forces might have had a further part in the formation of the rock-salt domes.

The flowage of salt from stratum into dome is a very slow process. Although movement is known to be going on at the present time, investigation of an open drill hole into a salt dome at a depth

[24] A. Nadái and A. W. Wahl, *Plasticity* (New York), p. 319.

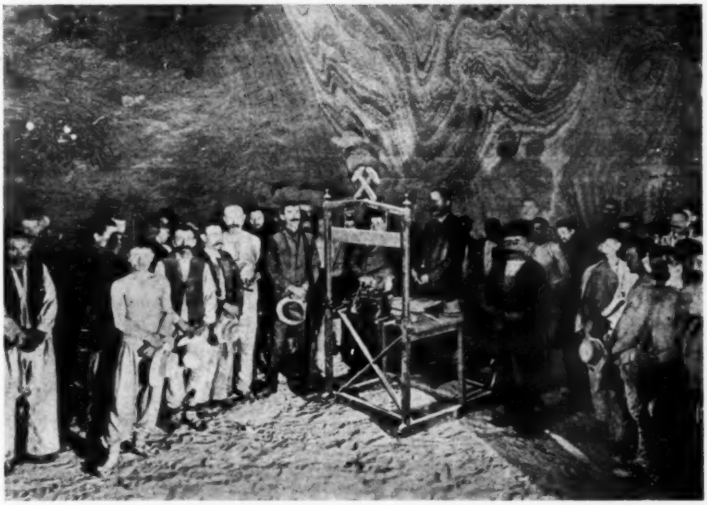

PLATE II.—Interior of salt mine, Maros-Ujvar, Transylvania, Roumania. Contorted banding of nearly pure salt is due to flowage from its original horizontal position deep in the earth.

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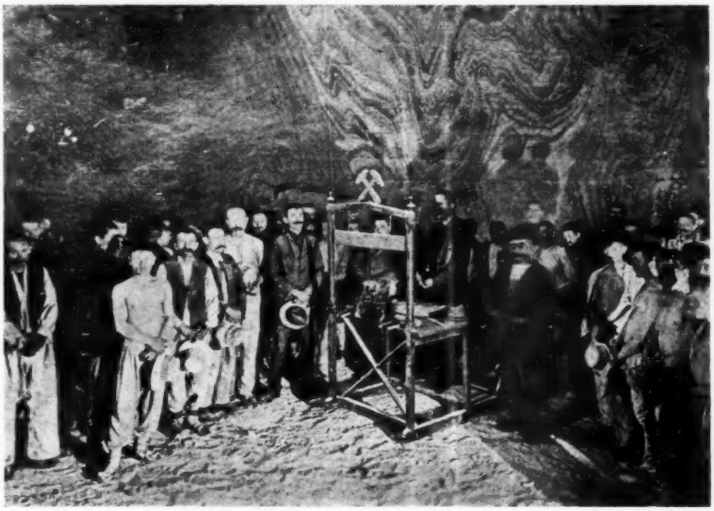


PLATE II.—Interior of salt mine, Maros-Ujvar, Transylvania, Roumania. Contorted banding of nearly pure salt is due to flowage from its original horizontal position deep in the earth.

of 5,960 feet in south Texas showed no distortion of the hole or salt while the hole remained open—a period of 9½ days.[25]

Salt domes of Germany.—Among the countries in which salt domes have been extensively studied is Germany. According to Romanes,[26] who describes the two obvious tectonic alignments in the North German plain:

> These movements . . . have not resulted in violent folding but have rather tended to develop intersecting series of faults and give rise to a structure which is, in the main, block faulting. . . . There is, however, a distinct tendency for the formation of domes along these two tectonic lines.

Mechanics of salt-dome genesis.—We are told by Stille[27] that, according to Harbort,[28]

> the latest upward movements at least are to be explained through the loading of the deeply buried salt by the younger sedimentary masses and the subsequent passage of the salt upward along fractures after the manner of a magma. Prominent students of salt domes such as Beyschlag,[29] Seidl,[30] and to a certain extent also Rinne,[31] share Harbort's conception.
>
> Arrhenius[32] attributed the upward movement of the salt mass to its lesser specific gravity, compared to that of normal rocks.

Minority views of salt-dome genesis.—Although Stille, in his critical article, differs in many points from early writers, he concludes that "orogenic thrust must be recognized as the cause of the upthrust." He, however, conceives the upthrust of the salt "as less the ejection of an especially *light* material than as that of an especially *mobile* mate-

[25] Personal letter from United States Bureau of Mines, June 4, 1932.

[26] James Romanes, "Salt Domes of North Germany," *Jour. Inst. Petrol. Tech.*, Vol. 17 (1931), pp. 352–58.

[27] Hans Stille, "The Upthrust of the Salt Masses of Germany," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 9 (1925), pp. 417–41.

[28] E. Harbort, "Zur Geologie der nordhannovererschen Salzhorste," *Monatsber. d. deutsch. geol. Ges.*, Vol. 62 (1910), p. 326; "Richard Lachmann's 'Salzgeschwüre'," *ibid.*, Vol. 63 (1911), p. 267; "Zur Frage der Aufpressungsvorgange und des Alters der nordwestdeutschen Salzvorkommen," *Kali* (1913), Heft 5, p. 112.

[29] F. Beyschlag, "Das Salzvorkommen von Hohensalza," *Jahrb. d. Preuss. Geol. Landesanstalt*, Vol. 34 (1913), Pt. II.

[30] E. Seidl, "Beiträge zur Morphologie und Genesis der permischen Salzlagerstätten Mitteldeutschlands," *Zeit. d. deutsch. Geol. Ges.*, Vol. 65 (1913), pp. 124 ff.

[31] F. Rinne, "Die geothermischen Metamorphosen und die Dislokationen der deutschen Kalisalzlagerstätten," *Fortschritte d. Minerologie*, etc. (Jena, 1920), Vol. 6, pp. 101 ff.

F. Rinne, "Physikal, Bemerkungen zur Tektonik der Erdbaumassen," *Norsk Geologisk Tideskrift*, Vol. 7 (1922), pp. 145 ff.

[32] Sv. Arrhenius, "Zur Physik der Salzlagerstätten," *Meddelanden fran. k. Vetenskabsakademiens Nodelinstitut*, Vol. 2 (1912), No. 20.

Sv. Arrhenius and R. Lachmann, "Die phys.-chem. Bedingungen bei der Bildung der Salzlager und ihre Anweddung auf geologische Probleme," *Geol. Rundschau*, Vol. 3 (1912), p. 139.

rial." He does not consider that the upthrust is due to the weight of the overlying beds on the salt stratum, but thinks the deformation is due solely to the mobility of the salt as affected by tectonic action along lines of structural weakness.

No two authors agree absolutely on the mechanics of salt-dome formation; but, in the writer's opinion, their differences are not impossible to reconcile. For instance, Schuh,[33] according to Barton, in reviewing Stille's article[34] and discussing the fundamental theories of mountain building, contraction and isostasy, and accepting the latter, decides that the form of the salt stock depends upon "the varying types of combination of fracture systems"; that is, he predicates "intersection of fractures" in contrast to Stille's "intersection of axes" and "axial nodes."

Correlation of theories.—The several arguments constitute mere quibbling in so far as the present purpose is concerned; for it is clear from all the articles that the salt masses pushed up along lines or points of weakness (either anticlinal or faulting) and that otherwise the salty stratum would have retained its bedded form, as in the hard rock formations of New York, Ohio, and Kansas, where tectonic pressure is known to exist, as in the Gulf Coastal Plain and in Germany, but where faulting is unknown.

Since weight of sediments alone is inadequate to deform salt masses underlying the consolidated strata of Devonian and Carboniferous ages in Ohio, New York, and Kansas, in contradistinction to the deformation that has taken place in faulted and unconsolidated sediments of Texas and Germany, for example, it seems equally clear that upward pressure likewise will be inadequate to cause deformation in strata of similar character.

Evidence derived from salt "hills."—Not all of the salt occurrences are mild ones, for Harrison tells us[35] that Kuh-i-Shur in south Persia is a cylindrical body of salt and gypsum and that the salt mass

> forms a nearly flat-topped hill rising 6,000 ft. above sea-level and 4,000 ft. above the neighboring plain. It rises 500 ft. above the highest point on the rim of the sedimentary rocks. . . .
>
> This salt-plug of Kuh-i-Shur is the nearest approach seen to a simple cylinder of salt. . . .
>
> Kuh-i-Kurdek is a roughly dome-shaped hill of salt of which the salt rises at least 1,000 ft. above the plain.

[33] Franz Schuh, "Beitrag zur Tektonik unserer Salzstöcke," *Kali*, Heft 1; "Die saxonische Gebirgbildung," I, II, *Kali*, Heft 8; "Salztektonik," *Kali*, Heft 17 and 18.

[34] Donald C. Barton, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 9 (1925), pp. 439–41.

[35] J. V. Harrison, "Salt-Domes in Persia," *Jour. Inst. Petrol. Tech.*, Vol. 17 (1931), pp. 300–20.

A

B

PLATE III.—Outcrops of rock salt constituting surficial phenomena of salt domes, Transylvania, Roumania.
A. Surface of Parejo salt dome.
B. Surface of Szováta salt dome.

Speaking of Kuh-i-Siah Tag-i-Girashi—a well shaped dome of salt, Harrison tells us that

the intrusion is a mile and a half in diameter and rises over 1,000 ft. above the Girashi plain.

The same writer continues:

Where a salt-plug has broken through and built a mound which stands up above the level of the surrounding country, it may happen that this is in static equilibrium; and as the weather tends to reduce the height of the hill a little more salt will be squeezed out to make good the wastage. The depth of the nucleus in the case of most Persian salt plugs is probably about 18,000–25,000 ft., so that the salt-hill should have a relief of about 2450–3400 ft. above the average level for approximate static equilibrium, since the salt has a specific gravity of about 2.2, and the column of sediments an average specific gravity of the order of 2.5. These heights are of the order observed for instance at Kuh-i-Namak-Shah Ghaib, although in most cases it would be difficult to choose a datum-line for the average level of the neighboring sediments.

Similar sub-aerial salt domes are known in several parts of the world, one of the most classical localities[36] being Jebel Usdum (Mount Sodom) in Palestine, the intrusive nature of which was first recognized by B. K. N. Wyllie, G. M. Lees, and K. A. Campbell in 1922.[37] This dome is 6 miles in length, has an average breadth of one mile, and the highest point is 720 feet above Dead Sea level. "The core of the mountain is massive rock salt, showing the banded structure so characteristic of most salt domes."

Application to Bradford problem.—Applying these remarks now to the question of the adequacy of 1,700 feet of Chemung and Cattaraugus shales and sandstones to withstand a subterranean pressure of 4,000 pounds per square inch, it should be explained that the following conditions, recognized in most if not all of the world's salt-dome areas, are dissimilar from any conditions that prevail at Bradford.

1. Salt domes have originated along vertical channels at the intersection of faults or at weak points in a fault system.

2. Salt domes (perhaps those of Utah excepted) are limited to areas of comparatively soft rocks (those of Cretaceous or younger age), generally unconsolidated, and the pressure required to lift, stretch, or rupture the consolidated Bradford rocks would be much greater than that necessary in Persia, the Gulf Coast, Germany, or the Mexican coastal plain.

[36] G. M. Lees, "Salt—Some Depositional and Deformational Problems," *Jour. Inst. Petrol. Tech.*, Vol. 17 (1931), pp. 265–66.

[37] B. K. N. Wyllie, "The Geology of Jebel Usdum, Dead Sea," *Geol. Mag.*, Vol. 68, No. 606 (August, 1931), pp. 360–72, 4 figs., 1 pl.

3. In my opinion the fact that salt domes are not known and probably do not exist in the consolidated formations of New York, Ohio, Ontario, and Kansas, where beds of rock salt are known to exist, is strong evidence that suitable centers of weakness, into which the salt might flow in course of long continued geological time, do not exist in these rocks and that the rocks themselves are solid enough to withstand the pressure that would be exerted from below. If either condition prevailed—(a) presence of centers of vertical weakness or (b) inadequate strength of rock materials—there would have been salt doming in these regions before now. From 10 to 50 times as great a period of geological time has elapsed in the areas of Carboniferous and Devonian rocks of northern states as has passed in the Tertiary areas. Yet no salt domes have formed in the entire salt-stratum areas of Ontario, New York, Ohio, and Kansas. If these strata have been able to resist a salt upthrust of thousands of pounds per square inch in some cases, they may be expected also to sustain themselves above a stratum influenced by water pressure.

ANALOGY FURNISHED BY BLOW-OUT GAS AND OIL WELLS AND VOLCANIC VENTS

Evidence derived from known blow-outs.—Since the strata overlying the Bradford sand are under a state of pressure from below, it was thought that some helpful analogy might be found in analyzing the possible effects of this upward pressure in localities where gas and oil wells or dry-ash volcanic craters have blown out on the surface. An active search was made to ascertain any such instances where the force of the upward pressure has been measured.

Blow-outs at Refugio, Texas.—The examples of this sort best known to the writer were near Refugio, in Refugio County, Texas, where a conspicuous fault of small displacement crosses a large creek in the western part of the field. Continuous escape of gas bubbles was noted in the water; and, less than a mile away toward the south in the direction of trend, a large gas well, drilled in the early days of the field, blew out, forming a flat-bottomed crater estimated roughly at 150 feet across and 50 feet deep. (These figures not checked against original notes.) It seems evident that the blow-out was caused by the near approach of the drill to a shallow sand into which gas had risen under high pressure and accumulated along the fault line. There are, however, no available figures on the depth of the sand responsible for the blow-out or on the pressure under which gas accumulated in it. The strata are soft, unconsolidated sands and clays of the Gulf Coast type, quite unlike those at Bradford. The near approach to

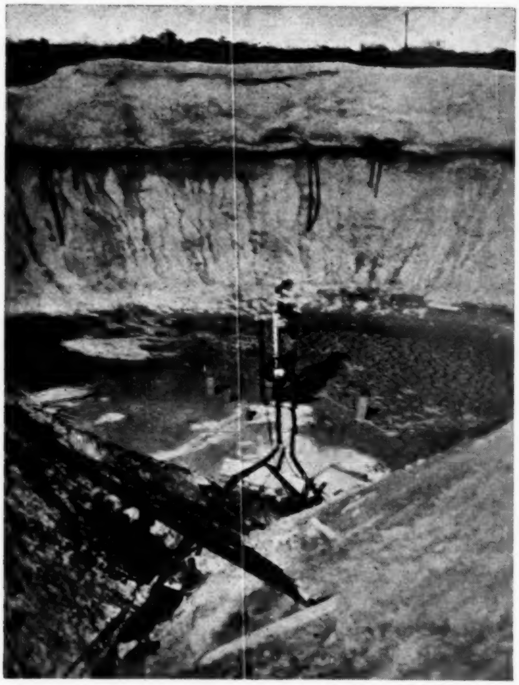
A

B

PLATE IV.—Gas escaping along fault plane on Blanco Creek, Refugio County, Texas.

A. Fault crossing Blanco Creek on west side of Refugio field.

B. Gas bubbles escaping along fault on Blanco Creek, evincing accumulations that caused blow-outs from shallow sands.



A

B

PLATE V.—Blow-out craters, White Point gas field, Texas.
A. Crater formed by natural gas blow-out, White Point Development Company's well No. 2.
B. Crater formed by natural gas blow-out, Rachel well No. 7.

securing positive evidence of upward pressures at Refugio served as encouragement to hunt for more definite information which it was hoped could be advantageously applied to Bradford.

Blow-outs in White Point and Saxet fields, Texas.—Several great blow-outs also took place during the development of the Saxet (Corpus Christi) and White Point fields in Nueces and San Patricio counties in southwest Texas.

In some cases the craters are 200 feet in diameter and as much as 80 feet deep. In order to determine pressure relationships, correspondence was undertaken with persons who might be able to furnish information. The nearest approach to a helpful reply comes from W. Armstrong Price.[38] He states that

> The only hint of an abnormally high pressure in the Corpus Christi district was in Gulf Production Co.'s No. 1 White Point Production Co. Fee. This well is supposed to have blown from the sand at 2175 feet, when it cratered, and the gauge showed 1175 pounds it is said. However, the driller on the well told me years later that the well was open to 3128 feet when this pressure was taken. The gate was not fully closed when this pressure was measured.
>
> The Gulf-Briggs Sterling 2 on Bay (State) Lease #683 and the White Point O. & G. No. 1 on White Point Production Co. Fee with the well named in the first paragraph fall along a N 30° E line (or near enough to one) which would pass between the two Houston Oil Co. Ragsdales (1 and 2) and along the west side of the field through blowouts and dry holes which could well be a fault line.

Considering all the fields that have been developed in Texas and the vast amount of oil taken out at depths of 1,000–7,000 feet under areas having comparatively unconsolidated overlying formations, there would have been numerous blow-outs if the strata themselves were not competent to sustain themselves under normal conditions.

Blow-out gas wells in Louisiana.—Louisiana has had many blow-outs, among which the most noted are in the Monroe and Richland gas fields.[39] In early days the Monroe field, in 1918 or 1919, had four active craters. In the initial well in the Richland field (England Planting Company well of Gulf Refining Company in Sec. 32, T. 17 N., R. 6 E.), in December, 1926, 1,108 pounds per square inch of gas were struck at 2,335 feet. Hill says[40] that

> Although gas was found in the shallow horizon before the main pay was discovered, this shallow zone later was charged with high-pressure gas from

[38] Personal letter dated July 6, 1932.

[39] H. W. Bell and R. A. Cattell, "The Monroe Gas Field," *Louisiana Dept. Conservation Bull. 9* (1921), 99 pp.

[40] H. B. Hill, "Crater Wells, Richland Gas Field, Louisiana," *U. S. Bur. Mines.*

crater wells producing in the lower formation. This extraneous gas at abnormal pressure made drilling through the upper horizon uncertain and hazardous in the crater area.

The wells, however, blew out in the main gas horizon at depths of 2,462–2,475 feet—these being known as the Thomason, Pardue, and Boykin "craters." Feazel-Pardue well No. 1, at the south end of the Richland gas field 4 miles south of Alta, completed August 3, 1928, had a depth of 2,450 feet and its reservoir pressure of 1,100 pounds per square inch was therefore a few pounds per square inch above the theoretically accurate pressure. It cratered, making a funnel-shaped hole 100 feet in diameter, filled with violently agitated fluid to within 30 feet of the surface, and great volumes of sand were blown over the surrounding lands.

Blow-out well at Dos Bocas, Mexico.—Many wells in Arkansas, California, and other parts of the world are known to have developed similar surface fissures and others have "cratered." Possibly the greatest crater ever produced by the "blowing out" of an oil well was at Dos Bocas, Taumaulipas, Mexico,[41] which, having reached a depth of 1,834 feet, entered a petroliferous formation charged with oil under immense pressure.

> In less than 20 minutes the ground round the well began to tremble and fissures appeared, some at a distance of as much as 250 feet from the well, from which oil and gas were discharged. . . . The well burned for fifty-eight days, during which time the oil consumed is estimated to have amounted to three million barrels. . . . In addition to oil and gas the well discharged immense quantities of water, at times at the estimated rate of one and a half million barrels per day, and with the liquid about two million tons of solid matter were ejected, a crater being thus formed which ultimately had an area of 117,600 square meters.

According to DeGolyer[42] there were in Mexico half a dozen wells of similar capacity of flow to that of the now famous Dos Bocas well; in every case 100–150 million barrels of oil were removed from the field and there is no recorded subsidence "and probably never will be any."

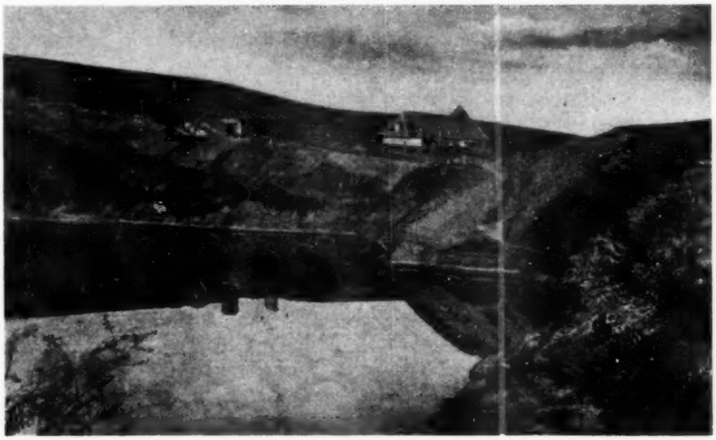
A historical Roumanian blow-out.—Few of the wells that have been blown out owing to intense gas pressure furnish us with any pressure measurements. One that has caused widespread discussion in Hungarian literature was the famous Sármás No. 2 well[43] 992 feet deep, drilled in 1911 in the field of that name in Kolozs County,

[41] Sir Boverton Redwood, *Petroleum*, Vol. I (1913), p. 95.

[42] E. L. DeGolyer, *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 75 (1927), pp. 738–39.

[43] F. G. Clapp, "Notes on Natural Gas Fields of Transylvania, Roumania," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 8 (1924), pp. 202–11.

A



B

PLATE VI.—A. Natural gas blow-out at Kis-Sármás, Transylvania, Roumania.
B. Caving of surface overlying salt mine, Torda, Transylvania, Roumania. Place of subsidence was entirely filled by salt water following disaster.

Transylvania, Roumania, the volume of which was 25 million cubic feet per day. The original rock pressure of this well was reported to be 384 pounds per square inch. After being closed with some difficulty[44] it was discovered that gas was emerging in many places from the ground, which is composed of exceedingly soft saliferous clay in which seepages are numerous in other parts of the basin.

The leakage was finally closed by laboriously cementing around the casing. After 3 months, however, a severe shock occurred one night, accompanied by a heavy rumble like that of an earthquake, and debris was thrown into the air at a point ½ mile from the well, while at the same moment gas commenced to escape at numerous points over many acres. The shock was felt in an elliptical area extending about 5 miles along the major axis of the dome. As in Texas and Louisiana, the Transylvanian strata are so soft as to make impossible any adequate comparison with Bradford conditions.

Dry-ash craters of New Zealand.—Another type of blow-out consists of craters formed along the line of a great fault in the volcanic region of North Island, New Zealand. These holes are hundreds of feet in diameter and scores of feet deep. They show no signs of lava, but have evidently been formed by an explosion of gas which collected under great pressure from below, but the amounts of pressure and depth are problematical. When a volcano "blows its head off" the principle may be similar.

Cause of cratering in gas fields.—It has been stated by Hill[45] that the unconsolidated formations in the fields of northern Louisiana and southern Arkansas are favorable to blow-outs and that other contributing factors are water sands at shallow depth.

Judging from what Price says about the alignment of certain blow-out wells in the White Point field and by observations in the Refugio field, it seems probable that gas ascended along faults and accumulated in shallow strata under abnormally high pressures. The geologist of the United Gas System, which operates extensively in that region, confirms this suspicion[46] in the following words.

> There are several cases, however, wherein gas has been allowed to escape from deeper reservoirs into shallower ones due to the careless drilling operations as well as poor completion. In this case abnormal pressures have been built up in very shallow horizons. In the case of the Refugio Field to which you refer, I do know that shallow water sands have been impregnated with gas through faulty drilling and completions.

[44] Ferenc Böhm, "A Kissármasi Gáskut Tomitése," in "A Magyar Mérök-es Epitéz-Egylet Közlönye," Evf. 7, Számabel, Budapest, 1912.

[45] H. B. Hill, "Crater Wells, Richland Gas Field, Louisiana," *U. S. Bur. Mines.*

[46] John S. Ivy, in personal letter dated July 6, 1932.

Application to Bradford problem.—The fact that upward gas pressure causes blow-outs in unconsolidated strata where a considerable excess of pressure is known or inferred renders the principle of the upward excess of pressure applicable also at Bradford. If strata in the northern Pennsylvania and southern New York field were of the soft unconsolidated nature of those mentioned, we could not hope for success in water pressuring at Bradford. But Bradford conditions are not at all similar; the strata are harder and many times more firmly consolidated. A logical reaction to be kept in mind during the reading of the following pages is that the absence of blow-outs of the Gulf Coast type in gas fields of Pennsylvania, New York, Ohio, Kansas, and Oklahoma is almost certain proof that the strata will sustain considerable excess of pressure—for such excess must exist, especially in some of the Oklahoma fields where numerous faults lead from deep-lying sands to shallow ones.

EVIDENCE FROM ACTUAL CONDITIONS PREVAILING IN OIL, GAS, AND WATER SANDS

Preliminary statement.—Another line of investigation which (it was suggested) might give decisive evidence as to the Bradford question was a study of the actual pressures known to exist in oil, gas, and water sands in certain fields as compared with the weight of the overburden. There are so many oil and gas fields and artesian water areas in which pressures are approximately known that, it would seem, no difficulty should exist in obtaining figures. Moreover, it was expected that somewhere in the world a locality would be found in which the net upward pressure is far greater than weight of the overlying strata; and, if so, this would be a criterion on which the Bradford question could be solved.

Accordingly a study was made of fields known to the writer and those of which he was able to get information through correspondence. Many had to be omitted from discussion because of insufficiency of data and this again brought to the front the carelessness of an average field staff in collecting exact data. In determining the bottom-hole pressures (reservoir pressures) in any field, two methods were applied —first to calculate the maximum possible reservoir pressure on a theoretical basis from known depth of well, approximate altitudes of surface and of the sand outcrop. The second method was to resort to reported reservoir pressures, either measured direct, as in the case of gas wells, or known as a result of measuring the closed-in well-head pressures and adding the weight of the oil or water column. When possible, the two methods were checked one against the other—generally with some degree of agreement in results.

Pressure conditions in Oklahoma City field.—The Oklahoma City field was one of the first investigated, because it was supposed that the great depth of wells and the probability that the outcrops are at considerably higher altitudes than the surface of the field would produce an excess of reservoir pressure above that of rock column. Considerable correspondence was undertaken to get the information, and helpful letters were received from L. G. E. Bignell, petroleum engineering editor of *The Oil and Gas Journal.*[47]

The original reservoir pressure in the Oklahoma City field is said by operators to have been between 2,400 and 2,500 pounds per square inch—at the bottom of "Wilcox sand" wells 6,200 feet deep—pressures having been checked in various ways.[48] The engineers of Phillips Petroleum Company, for instance, ran instruments to the bottom of the holes and corrected for sea-level datum. One well, however, had a top-hole shut-in pressure of 1,250 pounds, reached the sand at 6,270 feet and produced 40,000 barrels of 40.5° gravity oil and 30 million cubic feet of gas in 24 hours and therefore must have attained 3,400 pounds pressure at the bottom of the well, using the figure generally recognized in that field, that is, 35 pounds weight of oil and gas for every 100 feet of well column. There is, therefore, an excess of rock weight of more than 3,600 pounds over the reservoir pressure. The Oklahoma City field, therefore, despite its high pressure, has no criteria that will help us.

Pressure conditions in Refugio field, Texas.—The next field similarly considered was Refugio in southwest Texas because of its high pressure and the writer's knowledge that the outcrops of the producing sands lie at somewhat higher elevations than the surface of the field. Circumstances here are the existence of three or more principal producing sands at depths of about 3,700 feet, 5,500 feet, and 6,400 feet, respectively. The interesting point in regard to bottom-hole pressure is that, although the calculations were based first on elevation of the outcrop, with no deduction for friction, and in a second trial on computations from official well-head pressures, the last-named were the greater of the two sets for both the 3,700 foot sand and the 6,400-foot sand. Taking, however, the more conservative figures, the upward reservoir pressure for the 3,700-foot sand was found to be more than 1,900 feet less than weight of rock column and for the 6,400-foot sand it was more than 2,700 feet less than the weight of the rock column. It is evident that this field does not give us the criterion needed.

[47] Letters of May 31 and June 10, 1932.

[48] In May, 1932, this pressure had declined to about 2,000 pounds.

Pressure conditions in Turner Valley field, Alberta.—Again, it was confidently expected that the Turner Valley field, along the Rocky Mountain front in Canada, might give the expected conditions of excessive reservoir pressure due to sand outcrops at much higher elevation in neighboring mountains. A number of letters were exchanged with officials of the Canadian and Alberta governments, and helpful replies were received from the Petroleum and Natural Gas Division of the Department of Lands and Mines[49] of the Province of Alberta and the Turner Valley Gas Conservation Board.[50] It is reported that the depth of the productive limestone ranges from 3,628 feet to 6,010 feet, and that the closed-in well-head pressures of the gas-gasoline column several months after completion ranged from 1,325 to 1,885 pounds per square inch. Taking, for the purpose of determination, a certain well having 1,885 pounds pressure (3 months after its completion), depth of 4,970 feet to production and assumed specific gravity of the gasoline as 0.7368, the reservoir pressure is estimated as 3,200–3,700 pounds per square inch and the minimum rock column as 4,520 pounds. Consequently, on a conservative computation, the weight of rock column is 800–1,300 pounds in excess of the reservoir pressure.

Pressure conditions in Teapot Dome field, Wyoming.—A locality of which the writer can speak with authority is the Teapot Dome field, Wyoming, where the minimum depth of wells to the Second Wall Creek (principal producing) sand is about 2,750 feet, minimum altitude of the surface 5,150 feet, and maximum computed reservoir pressure 1,214 pounds per square inch or 1,425 pounds per square inch (according to whether, on the one hand, the height of sand outcrop on the flanks of the neighboring mountains, or, on the other, calculations on the basis of measured well-head pressures[51] were used as a basis for determination). The results of the two methods were deemed to be in fair agreement; but, as before, the determination from positive measurements proved the greater, even without considering frictional movement of water through the sand from the distant outcrop. The weight of the rock column was found to be 3,108 pounds per square inch; so that the excess of rock weight over reservoir pressure is 1,894 pounds on the basis of outcrop determination, or 1,683 on the basis of well-head pressures. Again the result was a surprise, for, after all, no excess of reservoir pressure exists over weight of rock.

[49] Personal letter from W. Calder, dated June 16, 1932.

[50] Personal letter from F. P. Fisher, dated June 22, 1932.

[51] With wells presumably full of oil but neglecting gas content (which of course is maximum weight of fluid rather than minimum).

Pressure conditions in Monroe field, Louisiana.—Since the Monroe field of Louisiana had been reported as one in which the actual reservoir pressure shows an excess over the theoretical figure, based on height of water column, a similar study for this field was desirable. Research was based on a recent treatise loaned by the United States Bureau of Mines; but, at the request of the Bureau, the figures had to remain in the background until the bulletin was published. Suffice, therefore, to say that there was no excess of upward reservoir pressure over weight of rock column; but, on the contrary, a deficiency, as in other cases, that in this instance amounted to more than 1,300 pounds per square inch.

Pressure conditions in Naft-i-Shah field, Iran.—A far jump was now made to the Naft-Khaneh field[52] on the boundary of Iran and Iraq, where it seemed reasonable to expect to find an excess of reservoir pressure, since the limestone carrying the oil crops out high on the mountains to the east. When in the locality several years ago, the writer secured official well-head pressures with respect to (a) an oil well in the center of the field and (b) a water well in its vicinity. Although unnecessary to go into details of calculation, it is safe to state that an excess of rock weight over reservoir pressure exists of approximately 650 pounds per square inch in the case of the oil well and about 450 pounds in the case of the water well. This is a fair agreement between wells several miles apart.

At Naft-i-Shah, again, the expected evidence was not found, and we must conclude that, on the basis of all evidence at hand from oil fields where greatest excesses of reservoir pressures were to be expected, there is no such excess; but, on the contrary, the rock column is heavier than the weight necessary to withstand the reservoir pressure even without allowing for strength of materials.

Pressure conditions in Dakota sand beneath central Great Plains.—It would seem incredible if there existed no place in the world where natural reservoir pressure, unaided by re-pressuring, is greater than the weight of the corresponding rock column. During a consideration of artesian conditions prevailing in the Dakota sand underlying the central Great Plains, in Nebraska, Kansas, North and South Dakota, and eastern Colorado, the possibility came to mind that somewhere in this vast water-bearing area, perhaps in the vicinity of the Rocky Mountains, a dome or anticline might exist under which the presure

[52] Although the original name of this field was Naft-Khanah, from oil discoveries near the locality of that name just inside the border of Iraq, the extension into Persia (or Iran, as the easternmost of those two counties should now be called) was recently named Naft-i-Shah by the Government and will doubtless continue to be so known.

TABLE I

COMPARISON OF NET UPWARD PRESSURES EXERTED IN VARIOUS FIELDS

("lbs." refers to pounds per square inch in all cases)

Name of Field	*Intake Water Pressure (lbs.)*	*Min. Depth Well (ft.)*	*Max. Depth Well (ft.)*	*Max. Alt. Sand in Field (ft.)*	*Min. Alt. Sand in Outcrop (ft.)*	*"Head" (Difference in Elev. of Sand) (ft.)*	*Min. Surface Alt. (ft.)*	*Min. Ht. Rock Column (ft.)*	*Max. Res. Pressure (lbs.)*	*Min. Wt. of 1" Rock Column (lbs.)*	*Net Upward Pressures ("More" or "Less" than wt. of Rock Column) (in lbs.)* More	Less
Oklahoma City	.....	6,200*	.....	....	.....	.....	1,200*	6,200*	3,400	7,006	.....	3,606
Turner Valley	.....	3,628	6,010	....	.....	.....	.....	3,600*	3,200–3,700†	4,520	.....	800–1,300
Refugio												
3,700 ft. sd.	.....	3,660	3,710	−3,520*	350*	3,870	140*	3,660	1,678‡	4,136	.....	2,458‡
		.....	.....	....	.....	.....	.....	.....	2,150§	4,136	.....	1,986§
5,500 ft. sd.	.....	5,470	.....	−5,030	370*	4,660	140*	5,470	1,990§	6,181	.....	4,191§
6,400 ft. sd.	.....	6,430	6,540	−6,400	400*	6,800	140*	6,540	2,948‡	7,282	.....	4,334‡
		.....	.....	−6,270	400*	6,670	160*	6,430	4,492§	7,282	.....	2,790§
Teapot Dome	.....	2,750	.....	+2,400	5,200	2,800	5,150	2,750	1,214‡	3,108	.....	1,894‡
		2,750	.....	+2,400	5,200	2,800	5,150	2,750	1,425§	3,108	.....	1,683§
Monroe	.....	2,100	2,300	140	.....	.....	70	2,100	1,050§	2,365	.....	1,315*§
Naft-i-Shah Oil		2,743	.....	−2,000*	.....	.....	700*	2,743	2,459§	3,100	.....	641§
Naft-i-Shah Water		.....	3,414	−2,700*	.....	.....	700*	3,414	3,382§	3,858	.....	466§
Bradford												
Max. pressure	1,440‖	1,400*	1,800*	....	.....	.....	.....	1,400	2,220	1,582	638	.....
Usual pressure	1,200‖	1,400*	1,800*	....	.....	.....	.....	1,400	1,920	1,582	338	.....
Desired press.	4,000‖ ¶	1,400*	1,800*	....	.....	.....	.....	1,400	4,780¶	1,582	3,198¶	.....

* Rough estimate.
† Assuming specific gravity of the gasoline produced as 0.7368 and the well-head pressure as 1,885 pounds.
‡ Based on approximate altitude of such outcrops.
§ Based on closed-in well-head pressures.
‖ Plus water-column of 779 pounds from wells 800 feet deep.
¶ Assuming that an intake pressure of 4,000 pounds might be used.
Note: In all of the above fields the assumption is made that a one-square inch water-column one foot high weighs 0.433 pound and that a rock-column of same shape and size weighs 1.13 pounds.

of the water, due to "head" of possibly 3,500–6,500 feet from outcrops on the mountain slopes, would be in excess of weight of the rock column. Profiles were drawn across the Great Plains from the Rocky Mountains near Denver east to central Kansas, and again from the Black Hills southeast to central Kansas.

In the central Kansas anticline, the loss of head due to friction is so great that there was no excess of water pressure. But, on the contrary, there are, in a few instances not far from the Rocky Mountain and Black Hill fronts, some domes in which the cover over the Dakota sand is moderate; so that a possibility exists that there the desired conditions may be found. If they could be found, and with high reservoir pressure, this would be a valuable help to prove that the artificial excess of reservoir pressure now existing at Bradford is, after all, not a solitary phenomenon. It might be desirable to conduct a systematic search, through reports of geological surveys, for evidence of this sort.

Application to Bradford problem.—The net result of the investigation of upward pressures existing in sands of many fields was therefore negative. The figures for the respective areas are summarized in Table I, in which Bradford stands alone as a conspicuous example of the sustaining power of 1,400–1,800 feet of rock strata overlying considerably greater pressures (normally more than 300 pounds but at times as much as 600 pounds) than the weight of the corresponding rock column.

EVIDENCES DERIVED FROM SURFACE SUBSIDENCES

Parallelism between subsidence and re-pressuring effects.—In searching for actually observed phenomena of a parallel nature, it was natural to consider cases of subsidences over mines and cavities. Evidently a similarity exists between the net upward pressures due to artificial re-pressuring on the one hand and the downward pressure exerted by an unsupported rock-column on the other. In the second named case, subsidences have actually taken place. In the first postulated instance the results are problematical and are to be determined. We may accordingly ask: are there mines or open spaces in the earth over which the weight of strata in pounds is similar to the net upward reservoir pressure in the Bradford sand; and, if so, what are the results? Under what circumstances did subsidences take place?

Classes of subsidence.—We need not concern ourselves here with natural compacting of the surface and consequent sinking of soft or unconsolidated ground. Nor need we consider the sinking of shore lines of the United States and other countries due to geologic causes

entirely removed from conditions in underlying strata. The classes of subsidence here recognized are the following.

1. Subsidences in oil fields
2. Subsidences over salt and sulphur mines
3. Subsidences over coal mines
4. Subsidences over metal mines
5. Subsidences over natural underground cavities

That such phenomena actually exist was an auspicious circumstance lending hope that the problem could be solved through their study; and a considerable search of existing literature, suppemented by correspondence, was conducted in order to procure needed data. Although the nature of the data accompanying descriptions of subsidence is seldom suitable for direct application to the problem in hand, some valuable information has been accumulated.

Subsidence in Goose Creek oil field, Texas.—The first example of subsidence that came to hand was from the Goose Creek field in Harris County, Texas, where, in 1918, Gaillard Peninsula, near the center of the field, was becoming submerged. Vegetation was flooded and killed and finally the entire peninsula disappeared beneath the water. In the small town of Pelley on the northern edge of the field cracks appeared beneath houses, across streets and through lawns and gardens. The continuance of movement resulted in a descent of the surface towards the oil field. Then changes in elevation amounted in places to as much as 16 inches and the movement was accompanied by slight earthquakes. Similar disturbances took place on Hog Island at the south end of the field, the downward movement in the direction of the field amounting to 3–12 inches. About 500 million cubic feet of material, or 20 per cent of the voids created by oil, water, and sand extraction were involved in the subsidence. The phenomena were fully established by re-running lines of levels to bench-marks set some years previously.

A discussion of this subsidence by Pratt and Johnson[53] resulted in varied suggestions[54] as to the cause, the divergence in view being a matter of scientific degree and not one affecting the main point. These writers were of the opinion that

[53] Wallace E. Pratt and Douglas W. Johnson, "Local Subsidence of the Goose Creek Oil Field," *Jour. Geol.*, Vol. 34, No. 7, Pt. 1. (October–November, 1926), pp. 577–90.

[54] L. C. Snider, "A Suggested Explanation for the Surface Subsidence in the Goose Creek Oil and Gas Field, Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11 (1927), pp. 729–45.

Wallace E. Pratt, "Some Questions on the Cause of the Subsidence of the Surface in the Goose Creek Field, Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11 (1927), pp. 887–89.

The facts presented above seem to justify the conclusion that the Goose Creek subsidence was directly caused by the extraction of oil, water, gas and sand from beneath the surface, beginning in the year 1917. In this connection it should be noted that the coastal plain beds at this locality consist largely of unconsolidated clays or gumbos, and that the sands occur in discontinuous lenses. Under such circumstances the removal of oil and water from the sands is not followed by a free flow of water into the pore spaces from distant localities, because the compact nature of the clays, which completely surround and isolate the sand lenses, prevents the ready flow of water. The pore spaces are therefore occupied by water draining in more slowly from the adjacent clays; and it is a well-known fact that the draining of clays causes them to become more compact. This, in turn, would permit subsidence of the overlying surface.

Other important factors, undoubtedly, are the reduction of pressure in the sand reservoirs from values of 1,000 or 1,200 pounds per square inch to atmospheric pressure, and the actual removal of sand itself from the reservoirs. In the reduction of moisture content, escaping gas has been a material factor. These factors have combined to produce a draining and a drying of the clays, with consequent shrinkage; and in the absence of competent beds to support the overlying deposits, the results have become apparent in a remarkable dishing of the surface of the Goose Creek field.

Oil is encountered sparingly in the Lissie formation at a depth of 500 feet, in quantity in sand lenses throughout the Fleming clays, and again in the upper part of the Oligocene. Commercially important production comes from depths of 1,000, 1,500, 1,700, 2,000, 2,400, 2,600, 2,800, 3,000, 3,300, 3,700, and 4,100 feet.

The geologic structure, as displayed in the Miocene and younger beds, is a low dome, while the Oligocene strata, beneath an unconformity, appear to be profoundly and intricately faulted. Goose Creek is not a salt dome of the ordinary type, for no salt has ever been encountered in drilling (at least, up to date of the present study).

The fact that Goose Creek is situated in a region of geologically young beds consisting of unconsolidated sands and clays, "only slightly more compacted than sea-bottom muds" (in the words of Pratt) renders this instance quite different from any condition at Bradford, where the strata are vastly older and firmly consolidated. Pratt continues:

> The sands are generally so soft that they flow into the wells, although locally and in part they may be cemented by calcium carbonate. Limestone occurs only as small concretions in the Beaumont and Fleming clays.

Another difference from Bradford conditions is the reported abundance of faulting in deep-lying beds at Goose Creek. Clearly the subsidence does not constitute a parallel circumstance to any possible relation between cause and effect at Bradford.

Subsidence in Sour Lake oil field, Texas.—Sellards has described[55] subsidence in the Sour Lake oil field in Hardin County, Texas, evinced by the formation of a "sink-hole," October 9, 1929, a second one, 3 days later, and a third break in the surface, January 20, 1930. Most of the subsidences took place, though very gradually, over a period of several hours. Two wells, near the sink, which had been producing oil, "went to water" on the day preceding the first subsidence.

Sour Lake is a salt-dome field in which the top of the salt approximates 900 feet from the surface. Above this salt lies a characteristic anhydrite "cap rock" containing some calcium carbonate. When examined by Sellards the subsidence had formed a cavity with a circumference of 1,400–1,500 feet and a maximum depth of 37.5 feet, involving about 90,000 cubic yards of material. He adds about 10,000 cubic yards of subsidence, evinced as depressions varying from 0.5 inch to 4.5 inches in depth, extending northeastward from the main depression for at least 1,000 feet and southward about the same distance, making a total loss of surface of approximately 100,000 cubic yards.

Sellards thinks (p. 379) that "the immediate cause of sink formation was the removal of solids," chiefly salt, in connection with oil production. But, he says

> a cavity has doubtless developed in the salt body, which continued enlarging until the thin, porous and probably cavernous cap-rock collapsed, permitting subsidence of the overlying sediments.

Discussion of this paper[56] brought out the fact that 73 million barrels, or 14 million cubic yards of petroleum had been extracted prior to that time. But, again, we have no conditions parallel to those at Bradford, for the Sour Lake strata are unconsolidated loose sands and clays as at Goose Creek—having no semblance or mechanical similarity to the Bradford rocks.

Subsidence in Jennings oil field, Louisiana.—In addition to the foregoing instances, another of the same sort is substantiated by Pratt,[57] namely, that of the Jennings oil field in Evangeline Parish, Louisiana, of which he is in the possession of

> affidavits and detailed statements from the late William Kennedy, a competent observer, as to the facts in the case. These statements reveal that the surface subsided over an area of several acres, immediately overlying the salt dome that marks this field. It took place following the peak of development,

[55] E. H. Sellards, "Ground Subsidence at Sour Lake, Texas," *Min. & Met.*, Vol. 11 (August, 1930), pp. 377–80.

[56] George S. Rice, *Min. & Met.*, Vol. 11 (August, 1930), p. 379.

[57] Wallace E. Pratt, *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 75 (1927), p. 740.

and it was made evident that a lake formed in the depression which resulted from the subsidence. . . .

. . . .

Of course, the Jennings subsidence may be a little different in character from the Goose Creek subsidence, since the Jennings field has a known salt dome not too deeply buried, whereas in the Goose Creek field the deepest hole has never penetrated any salt. The subsidence at Jennings, therefore, might possibly be caused by the solution of the upper part of the salt.

The Jennings field, like those of Sour Lake and Goose Creek, lies in the Gulf Coast region of unconsolidated strata. No condition and nothing that has taken place there forms a parallel to anything at Bradford.

Subsidences overlying California oil fields.—A popular article[58] asserted that the surface of the Signal Hill oil field in Los Angeles County, California, has settled and that the surface of the Santa Fe Springs field in the same county has sunk 6 inches. Inquiry at the Division of Oil and Gas of the Department of Natural Resources of the State of California brought a reply that "this office has no information whatever pertaining to the matter."

Inquiry from professional colleagues resulted similarly in lack of information, although one geologist[59] replied that he

would not be surprised at such action in those fields where considerable beds of sand have come out with the oil. Our old Sunset field is the most typical example of this fact.

Notwithstanding the vast amount of oil that has been taken out of California fields, there seems to be no official record, according to Patterson,[60] of subsidence at the surface "that has been caused directly by the extraction of oil." He tells us, however, of some "sub-surface subsidence" owing to extraction of sand, namely, in the Midway oil field in Kern County. An oil sand 300 feet thick and 1,300 feet deep underlying 126 acres was estimated to average 13,068,000 cubic feet of contents per acre. After a period of four years 379,471 barrels of oil had been recovered, with which 703,485 cubic feet of sand had come to the surface. Of this quantity 184,540 cubic feet of sand had been pumped from one well alone. In the process of drilling neighboring wells, cavities were found in some places at the top of the sands, and these had to be filled artificially—in one case with as much as 50 tons of rock. The fact that actual cavities of 50 tons' filling capacity (about 270 cubic feet) can exist at depth under unconsolidated sedi-

[58] Sterling Gleason, "Haunted Oil Fields Puzzle Geologists," *Popular Science* (July, 1932), pp. 14–15 and 103–4.

[59] Ralph Arnold in personal letter, dated July 11, 1932.

[60] R. C. Patterson, *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 75 (1927), pp. 740–42.

ments, such as those of California, is a favorable sign for sustaining power of more resistant rocks like the Chemung and Cattaraugus shales at Bradford.

Application of oil-field subsidences to Bradford problem.—When we consider the vast amount of oil, gas, water, and sand taken out of unconsolidated strata in Texas, Louisiana, and California, it is strange that more cases of subsidence are not known. Aside from the two Texas instances, one in Louisiana, several more or less inconclusive cases in California, and one or more noticeable subsidences in Venezuela, there seem to be no well authenticated instances of the sinking of the surface in oil fields. In view of the vast number of fields developed in unconsolidated strata, this is indeed surprising. In the more firmly compacted strata of Oklahoma, Kansas, Pennsylvania, West Virginia, and New York, no record of subsidence exists as would certainly be the case if the 1,000–5,000 feet of sandstones and shales were incompetent to sustain themselves over a vast underground cavity. If it be said that the subsidences have only occurred where lenticular nature of the sands causes a vacuum on removal of the oil, the answer is that in West Virginia no water is found in the sands; neither has there been subsidence. The usually consolidated Paleozoic rocks in our northern fields seem competent to hold over broad areas.

Subsidence over salt dome at Big Hill, Matagorda County, Texas.—In considering subsidences over salt mines, we are told by Thom[61] that

> The salt dome formerly known as Big Hill, Matagorda County, Texas, was formerly marked by a mound, which stood 35 feet or more above sea level. During the extraction of sulfur by the Frasch process, a pond has been developed over at least a part of the site of the former hill, indicating a total subsidence of perhaps 35 or 40 feet.

Like the Sour Lake and Goose Creek oil fields, Big Hill lies in a vast region of unconsolidated strata, and subsidence over an open cavity was to be expected.

Subsidence over workings of bedded rock salt at Hutchinson, Kansas.—During extraction of salt as artificial brine about the year 1915 from a depth of 340 feet at Hutchinson, Kansas, traces of subsidence[62] took place and proved to be measurable. An estimate of the amount of salt that had been removed was 31 million cubic feet from 5 wells. The first evidence of instability was the appearance of cracks in walls of the Court House, although the sticking of its doors had previously

[61] W. T. Thom, Jr., *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 74 (1926), p. 187.

[62] C. M. Young, "Subsidence Around a Salt Well," *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 74 (1926), pp. 810–17.

been remarked. City and County engineers immediately commenced observations with the result that a series of ground cracks was found, roughly outlining a circle 600 feet in diameter. In one place a pavement buckled along two lines. Observations on the fluid level of a sewer showed a difference in level of 6 inches. County engineers reported the existence of horizontal movement about 2.5 inches in the schoolhouse. In another place vertical movement amounted to 2.5 inches in 3 months, and in no instances did measurements show more than 3 inches of vertical movement.

Since the Hutchinson salt mines are situated in a region of consolidated rocks, it is evident that the conditions are somewhat similar to those at Bradford. Nevertheless, the depth at Hutchinson is so shallow, involving only 340 feet of strata, or less than 400 pounds pressure per square inch, that no lesson drawn from Hutchinson can be applied at Bradford.

Subsidence over salt mines in Cheshire, England.—An elaborate volume[63] by Calvert treats (pp. 304–84) of various subsidences that have taken place in the Northwich district of England from 1750 to date. Even prior to that time, sinking of the surface had been reported near Combermere in 1533, at Bickley near Malpas in 1657, and at Weaver Hall near Winsford in 1713. As opposed to the considerable depths which we are considering at Bradford, however, the principal salt beds in Cheshire lie only 150–250 feet from the surface. As they are more than 100 feet in thickness, the cause for subsidence is quite evident, that is, caving over large cavities found by solution of salt. These salt beds are of Mesozoic age and are therefore overlain by unconsolidated marl which, by its nature, subsides easily into the cavities formed.

Application of salt-mine subsidences to Bradford problem.—The writer's work in Roumanian fields likewise brought to light cases of subsidence over a number of salt mines, owing to mining and solution of the salt underneath very loose unconsolidated sands and clays. Photographs are in his possession of railway tracks suspended in air soon after such subsidences. These occurrences, like those at Hutchinson and Cheshire, are over mines that extend only a few hundred feet below the surface. No subsidence is reported throughout areas of New York, Michigan, Ohio, and Ontario where salt has been removed in the form of brine, or in France where it is mined by shafts and galleries. To sum up, the fewness of subsidences over salt is the remarkable fact—not some occurrences of subsidence throughout the whole world.

[63] A. F. Calvert, *Salt in Cheshire* (London and New York, 1915), 1158 pp. and illus.

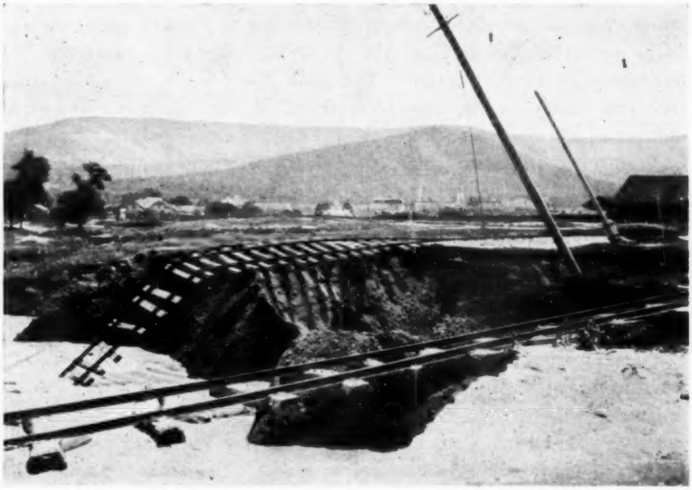


PLATE VII.—Caving of surface overlying salt mine, Maros-Ujvar, Transylvania, Roumania. Both views show sagging and breaking of railway tracks in the year 1913 over deep holes caused by sinking of surface during drowning of mine after cave-in.

Subsidences in Oklahoma coal fields.—Coming now to manifestations over coal mines, a sudden subsidence on September 4, 1914, in Mine No. 1 of Union Coal Company at Adamson, Oklahoma, has been described by Rutledge.[64] The seam was 5 feet thick and inclined from the surface at an angle of from 22° to 30°. The overlying strata consist of Pennsylvanian shales and sandstones. Surface cracks had been observed, it is said, nearly a month previously, but the collapse came suddenly. Although the mine workings are immediately beneath the streets and buildings of the mining town of Adamson, business was not disturbed by the subsidence. Cracking was interpreted as due to leverage in the 800–1,700-foot breadth of overburden.

The same observer describes a subsidence at Henryetta, Oklahoma, where, early in 1917, underground operations began to affect the Irving School (a brick building about 70 feet square) and the trouble increased until 1922, when the structure was declared unsafe and had to be torn down. The school stood directly over Mine No. 2, belonging to Crowe Coal Company (formerly Whitehead Coal Company), of the Henryetta coal seam, 3 feet thick and 165 feet below the surface. The rooms of the mine are said to have been as wide as 45 feet in some cases and were almost all 40 feet wide. The overlying strata consist mostly of shale and thin sandstone beds—the roof of the coal being "fairly good in character." Although the building stood

> on one of the streets of a city of about 16,000 population . . . there was no apparent inconvenience to the citizens . . . and traffic on the streets was not disturbed.

The dip of the coal seam is not reported, but the observer states that

> two sections of the cornice had apparently been separated by forces acting in a horizontal direction. In many cases the horizontal component appears to be stronger than the vertical.

Subsidences in Illinois coal fields.—Subsidences are referred to by the same observer in Illinois coal fields. In one place the overburden of about 600 feet covers a horizontal seam 10–12 feet thick. He states that 50 per cent of the seam was mined and the remainder left as pillars. At another place an 8–10-foot horizontal seam lies 500 feet from the surface, yet the roof broke and the surface sank about 3 feet.

In Illinois, as opposed to many coal-mining regions where subsidence has been noticed, the strata lie comparatively flat; still subsi-

[64] J. J. Rutledge, "Examples of Subsidence in the Oklahoma Coal Mines," *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 69 (1923), pp. 406–13.

dence takes place, as has been explained by Young.[65] Perhaps one reason why serious cracks have not been reported more frequently in this state is the existence of glacial drift from 25–200 feet thick overlying the Carboniferous "Coal Measures."

It is made quite evident that surface cracks are due to tension and shear and are merely one manifestation of more extensive subsidence in beds immediately overlying the mines, setting up stresses in the respective beds from the coal upwards. Young explains (p. 31) that "If each stratum is regarded as a beam, a portion of the beam will be in tension and a portion in compression." But, he states that

> The ordinary mine roof is weaker in tension than in compression. Tension cracks may be found in the mine roof in the zone where tension is greater than tensile strength of the rocks; and similarly, upon the surface, tension cracks may be found in the rocks or in unconsolidated surficial beds in the tension zone.

Illustrations are given (pp. 32–37) of tension cracks 4–10 inches wide at Streator, Illinois. Young adds that "a mine roof is likely to fail first in tension."

In the same state, holes have been found in the surface, structures have been tilted (p. 65), and large tracts of land flooded owing to depression of the surface (p. 48). Possibly more studies have been conducted on subsidence by the State of Illinois and the United States Bureau of Mines than by any other agencies.[66]

Subsidences in Pennsylvania anthracite mines.—Numerous subsidences have taken place in the anthracite mines of Pennsylvania where eleven principal coal beds exist—highly inclined. As examples, may be mentioned[67] the "complete crush in the Dunmore bed at Scranton, 750 feet below the surface"—mined by the room-and-pillar method. "It was overlain by nine beds of coal, four of which had been mined seven years before, and had been closed by squeezes." This subsidence in the lower coal bed caused surface subsidence of 1.5–2 feet, but it "did no material damage to surface structures." A detailed study of subsidence in strata overlying the anthracite seams was made by the United States Bureau of Mines[68] after "popular sentiment was

[65] L. E. Young, *Illinois State Geol. Survey Coöp. Coal Min. Ser., Bull. 17* (1916), 112 pp.

[66] L. E. Young and H. H. Stoek, "Subsidence Resulting from Mining," *Univ. Illinois Eng. Exp. Sta. Bull. 91* (1916), 205 pp.
L. E. Young, "Surface Subsidence in Illinois Resulting from Coal Mining," *Illinois State Geol. Survey, Coöp. Coal Mine Ser., Bull. 17* (1916), 112 pp.
G. A. Herbert and J. J. Rutledge, "Subsidence Due to Coal Mining in Illinois," *U. S. Bur. Mines Bull. 238* (1927), 59 pp.

[67] E. T. Connor, *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 69 (1923), pp. 419–20.

[68] William Griffith and E. T. Connor, "Mining Conditions under the City of Scranton, Pennsylvania," *U. S. Bur. Mines Bull. 25* (1912), pp. 1–71.

brought to a focus by a settlement in Hyde Park, on August 29, 1909." Many references on anthracite subsidence at Scranton have appeared in the literature. On account of the considerable number of coal seams, range in depths, inclination of the beds, folding, and faulting, the Scranton results can not be quoted to determine what might happen at Bradford in flat, unbroken strata with pressure conditions reversed.

Summary of subsidences over American coal mines.—The numerous mine subsidences that have taken place at various times naturally led engineers to consider the subject as an imminent danger in mining, and a number of fairly exhaustive discussions have been held by engineering societies. Although the vast majority of recorded instances are not pertinent to the present problem on account of shallow depth of operations or insufficiency of exact data given, some valuable particulars have been gleaned from the discussions.

In a symposium held by the American Institute of Mining and Metallurgical Engineers at its New York meeting in 1926, an attempt was made to obtain as complete information as possible on subsidence due to mining. The report of a committee that had previously been appointed, together with appendices and discussion, occupying 75 pages[69] of the *Transactions*, enumerates and describes 49 cases of subsidence in foreign mines and 64 in mines in the United States. A study of these proved of only slight value.

According to the discussion and tables it was apparent that in the United States there is no record of a subsidence over mines that lie more than 720 feet below the surface. Subsidences ranging from a few inches up to 20 feet occur, however, in shallower mines— the maximum being apparently over those that lie not more than 80–120 feet below the surface, according to bulletins of the Illinois State Geological Survey and the University of Illinois.

It seems unnecessary to study the numerous records of trifling subsidence in shallow mines, for the comparatively small number of such occurrences in deeper mines indicates that the overburden is (in this country) sufficiently strong to sustain itself in most cases even after withdrawing deep-lying pillars. In the deepest mine mentioned, the weight of the overlying rock must have been somewhere between 750 and 900 pounds per square inch; whereas, in the cases evincing 20 feet of subsidence, the weight could not have been more than 350 pounds per square inch. This indicates that thickness of the rock column is an advantage and that 1,400 feet of Chemung and Catta-

[69] "Report of the Sub-Committee on Coal Mining to Committee on Ground Movement and Subsidence," *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 74 (1926), pp. 734–809.

raugus strata at Bradford may more than offset the excess of contemplated pressure as opposed to that in reported American mine subsidences.

Subsidences over coal mines in Lancashire, England.—All of the subsidences in Lancashire, England, reported by the American subsidence committee[70] are said to overlie mines in which the longwall method of mining is used, as opposed to the room-and-pillar method used in most American mines in which subsidence is known. In Lancashire mines the gateways are 9 feet wide with 45-foot centers, and the space is "well packed"—all of the coal being removed. The uppermost strata consist of 40–60 feet of glacial drift, having a nearly level surface, underneath which lie 400–3,300 feet of Carboniferous beds of which about 80 per cent are shales and 20 per cent sandstones. The dip of the strata was 12°–20°. The "draw" or line at which caving commenced was on a vertical angle of 5°–22°, reaching 80–1,290 feet ahead of the workings. In the *Coal Age*[71] appears a summary of testimony given by T. A. O'Donahue asserting a subsidence of 1.5–3 feet. Because of the excellence of the ordinance (government) bench marks, the evidence was perfect.

Discussion of subsidences over coal mines in Great Britain.—Discussion of this subject has been voluminous. Many writers accept the "dome theory" by virtue of which subsidence tends to reach the surface, not by vertical planes, but by "domes of subsidence," converging at an angle upward. According to Brychan:[72]

> Mr. C. E. Rhodes mentions a case known to him of the pull of workings 800 yards in depth reaching the surface 200 yards in advance of the working face, being an angle of draw of 14° from the vertical.

This was apparently in a flat-lying coal bed.

Havelock[73] experimented with subsidence above the Beeston coal seam (thickness, 4–4.75 feet, lying 1,650 feet from the surface) near Castleford, Yorkshire, running levels repeatedly—in May, 1911, October, 1912, September, 1913, and September, 1914. The settlement amounted to 0.79 foot the first year, had reached 1.52 feet at the end of the second year, 2.13 at the end of the third year, and 2.25 at the end of the fourth year after working. Havelock agreed that

[70] *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 74 (1926), pp. 734–96.

[71] "Subsidence, How Far It Extends, Its Depth and Rapidity of Movement," *Coal Age*, Vol. 26, No. 16 (October 16, 1924), p. 557.

[72] "Subsidence in Mine Working," *Sci. and Art of Min.*, Vol. 29 (1919), pp. 375 and 407.

[73] G. C. H. Havelock, *Col. Guardian*, Vol. 121, No. 3133 (Jan. 14, 1921), pp. 109–10.

the effect of subsidence is more in the nature of a "draw" than a vertical downward depression. He asserts that in South Yorkshire, where mining was 1,200–2,100 feet deep, the pull would always be felt at the surface in advance of the mine headings by about one-sixth to one-tenth of the depth.

In the case of the South Kirby Colliery in Wales,[74] the surface was lowered 3.47 feet, as a result of removal of pillars in a 4.25–4.75-foot coal seam lying 2,108 feet below the surface. The subsidence began 4 years after the withdrawal of pillars and ceased 11 years, 8 months after their withdrawal. Other cases of 1.34 inches to 3.16 feet of subsidence in British mines are reported to have occurred owing to pillar withdrawals 1,000–2,410 feet below the surface.[75]

Subsidences in Belgian and German coal mines.—Coal mine subsidences in Belgium are said by Thiriart[76] to have commenced as long ago as 1838, when the effect on a house was investigated by Toilliel. In 1858 subsidences in that country were studied by Gonot.[77]

Connor[78] reports subsidence in the Krupp mines at Essen, Germany, and states that, although no levels had been run on the surface, the German engineers estimated that the surface had subsided under a part of Essen:

> about 8 ft. after ten or twelve beds of coal had been extracted, the aggregate thickness of the coal being about 40 ft. They said that there was no noticeable effect upon the surface structure.

An exhaustive search of the literature of European examples has not been made, but Von Sparre[79] submitted formulas for the amount and time of sinking and position of the first cracks, taking into account depth, inclination of beds, etc. Thiriart goes into the detailed mathematics of subsidence and the theories of various engineers regarding it.

Subsidences over coal mines in India.—Subsidence in India was studied by a committee about 1915 and the results were summarized in 1922.[80] Among other points considered was the effect of inclination

[74] *Univ. of Ill., Eng. Exp. Sta., Bull. 91* (1916), 205 pp.

[75] *Loc. cit.* and *Inst. Civil Eng.* (1898), Vol. 135, p. 116.

[76] Léon Thiriart, "Les affaisements du sol produits par l'exploitation houillere," *Ann. des Mines de Belgique*, Vol. 17 (1912), pp. 3–62.

[77] Gustave Dumont, "Des affaisements du sol produits par l'exploitation houillere," *Réponse de l'Union des Charbonnages, Mines et Usines* (1875).

[78] E. T. Connor, *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 69 (1923), pp. 419–20.

[79] See Dumont's article.

[80] Report on the "Subsidence Committee of the Mining and Geological Institute of India," *Trans. Min. Geol. Inst. India*, Vol. 16 (April, 1922), pp. 145–66.

of a coal seam on the position of the surface disturbance, neglected in most studies elsewhere. The committee confirmed an announcement that had already been made[81] as follows.

A. Subsidence extends over a greater area than that excavated.

B. The effects of excavation are due to two forces, a vertical component due to the weight of the rock unsupported and a horizontal component due to a cantilever effect on the adjoining strata. The "draw" of extension of effect outside the surface areas vertically above the excavated area is due to the horizontal component.

C. In cases of inclined seams the angle of break lies between the normal and the vertical, or, in other words, the effect of the inclination is to shift the subsided area towards the dip.

D. The amount of subsidence varies with the nature of the strata and the depth.

E. Conditions and factors effecting the result vary so much that no definite and universal rules can yet be applied.

Relation of coal mine subsidence to geologic conditions at the locality.—Considering the world as a whole, the number of authenticated instances of subsidence may seem appalling. Yet, when bearing in mind the great number of mines throughout the world, possibly the more common absence of subsidence may be more surprising. When one studies the records of subsidence, he becomes impressed with the fact that every subsidence has a cause; and it does not mean that, because a mine has been badly operated, caving is sure to follow. Rutledge[82] tells us, referring to Illinois, that

In the longwall fields, the method of mining being longwall advancing, the mine workings have passed under fairly good sized cities, canals, railroads and navigable rivers, and no great damage has been done to buildings and highways; in fact, some old citizens of the towns overlying the longwall mines do not believe that subsidence of the surface is a result of longwall mining as practiced in northern Illinois.

And, again, from Great Britain comes the testimony of Havelock[83] that

Subsidence, although an interesting subject, is at the same time a most aggravating one. It is the one subject kindred to mining which cannot be studied from a text book. It is so erratic, even when circumstances appear to be the same, that it defies the scope of the scientist and mathematician alike, and no formula exists regarding it, but has its conditions and limitations.

Relation to faults, joint cracks, dikes, and disturbed strata.—It should

[81] George Knox, *Trans. Inst. Min. Eng.*, Vol. 44 (1913).

[82] J. J. Rutledge, *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 69 (1923), pp. 406–13.

[83] G. C. H. Havelock, "Subsidence Due to Coal Mining," *Col. Guardian*, Vol. 121, No. 3133 (January 14, 1921), pp. 109–10.

be further stressed that a great majority of the subsidences can be proved, on engineering and geological study, to have a definite cause. Perhaps one of the most common factors is the existence of faults, joint cracks, and crushed zones which are absent at Bradford. The Indian Committee reported[84] that

> Dykes and faults have a definite effect on the position of the subsidence, the subsidence shifting towards them.
>
> The area which can be excavated before a surface break occurs is remarkably large [and] in seams thicker than 16 ft. at the depth of not exceeding 400 ft., with sound adjacent pillars, and no abnormal circumstances such as dykes, faults and overlying seams goafed, an area of 10 bighas ($3\frac{1}{2}$ acres) can be extracted before a surface effect appears.

The committee goes on to say (p. 149):

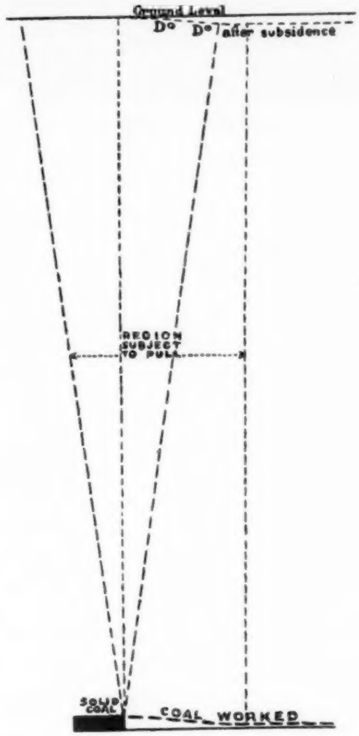
> The great strength and homogeneity of Indian coal measure sandstones is shown by the largeness of the area which will stand unsupported after the extraction of a coal seam of considerable thickness. Take Case No. 1: Fifteen feet of coal have been extracted over an area of twenty-four bighas (or 590 ft. by 590 ft.) and yet no surface effect has occurred. The weight of rock undermined as a result of the extraction of the coal is ten and a half million tons. The calculated shearing stress on the adjoining and unsupporting strata is 10 tons per sq. ft., or 160 lbs. per sq. in. The safe limit of shearing stress of sandstone is given by one authority as 150 lbs. per sq. in.

Relation to inclination of the strata.—It seemed worth while to study the subsidences with reference to inclination (dip) of the coal beds where recorded by the American subsidence committee.[85] Although data are fragmentary it was found that subsidence in level strata was only recorded over mines 600 feet or less in depth or where the depth was not given. It was found that the coals in mines 1,740–2,970 feet deep over which subsidences took place in Lancashire were inclined from 12° to 20° with the horizontal; that the coal seams in Yorkshire at depths of 2,140–2,410 feet have grades of 8.3 per cent, although subsidence took place over one English coal bed characterized as "about level" which lay only 324 feet below the surface. The inclination in Indian mines ranged from 16.7–18 per cent at depths of 300–857 feet. It is to be regretted that, even as regards the United States, the Subsidence Committee's report gives few data on rate of dip, and the majority of other articles seems to have refrained from mentioning this important point.

The predominance of subsidence in regions of high dips is manifested in the Pennsylvania anthracite fields, at Adamson (Oklahoma) and in Lancashire (England).

[84] George Knox, *Trans. Inst. Min. Eng.*, Vol. 44 (1913).

[85] *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 74 (1926), pp. 778–80.



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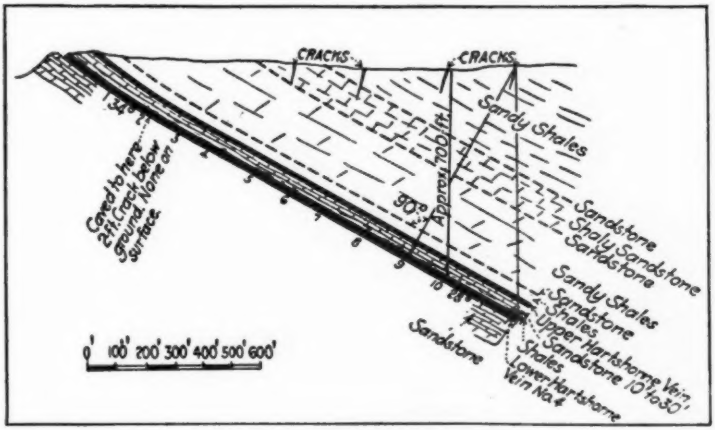

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PLATE VIII.—Illustrations to explain nature of subsidence over coal mines.

A. Theoretical subsidence over horizontal coal seam (after S. R. Kay, *Proc. Inst. Civil Eng. London*, Vol. 135, 1899, p. 118).

B. Subsidence over inclined coal seam in Oklahoma (after J. J. Rutledge, *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 69, 1923, p. 408).

After reading the various reports on subsidence, it is evident that there is a strong tendency toward subsidence over mines of which the seams have a considerable dip, which should be expected, since such mines furnish a leverage and cantilever effect that may go beyond the safe breadth of workings. Where coal mine subsidences are not due to the existence of faults or dikes, extreme shallowness, or presence of outcrop, it seems very likely that they have been caused by the considerable dip of the strata, and this is even more likely in cases where steeply dipping coal beds that intersect the surface are mined downward along the dip. The Indian Committee said (p. 149):

The instability of pillars in thick seams lying at steep angles may be emphasized. . . .

The contrast of such conditions with those at Bradford is great, but it must be acknowledged that some subsidences have occurred in regions of flat-lying rocks, as in Illinois.

Relation of subsidences to depth of mine.—The occurrences of subsidences were made a subject of discussion by the North of England Section of the Institution of Mining Engineers, but there seems no certainty that the question was settled. One British opinion is that the greatest subsidences are over shallow mines, and this view seems to have widespread backing For instance, a great majority of subsidences, including numerous instances not mentioned here, are over coal mines only 50–120 feet from the surface. The greatest depth reported of a United States coal seam that caused subsidence is 720 feet, although information is not complete and published articles are deplorably lacking as to such important particulars as depth inclination and solidity of strata.

The United States Bureau of Mines states[86] that

It is difficult to obtain precise data in many known cases of subsidence. Even when the operating companies do have this information, obtained by establishing lines of monuments, they do not care to disclose it because of legal complications from damages claimed by surface owners.

There is, according to the Bureau of Mines, no "harmless depth," as was formerly believed, but the amount of subsidence generally decreases with depth due to the spreading of the effect.

The maximum depth at which Indian subsidence was noted was 890 feet, in the Sibpur 14-foot seam, having an inclination of 1:12. The greatest recorded subsidence in this case was 12 per cent of the thickness of the seam. There was no surface movement recorded over a period of 4 years. In another seam (Dishergarh), however, lying at

[86] Personal letter dated July 22, 1932.

a depth of 857 feet and having a thickness of 15 feet, an inclination of 1 in 5.5, subsidence occurred (Case XV).

In describing subsidences in British mines, Kay[87] remarked that

> Breaks in the strata find their way to the surface from a depth of 100 yards unless the thickness of the seam worked is considerable and there is a thick bed of rock intervening. The author is aware of instances of coal-seams up to 5 feet in thickness being worked out beneath canals and rivers at this depth, without the slightest percolation resulting. . . . The time taken for complete subsidence at this depth may be between 2 years and 3 years. . . . In the case of mines more than 100 yards in depth, the subsidence follows more slowly, the greater the depth and the less the thickness excavated, as might be expected.

O'Donahue stated that "the greater the profundity of the seam, the less pronounced the sag."

It is the considered opinion of the writer, therefore, that the flat-lying strata, absence of faults or dikes, and considerable depth of consolidated shales and sandstones overlying the Bradford sand are circumstances that render the problem of that field susceptible to a satisfactory solution even in the face of the subsidences mentioned and of others that could undoubtedly be brought up.

Subsidences over metalliferous deposits and tunnels.—Caving overlying an ore-body mined at a depth of 300 feet at Franklin, New Jersey,[88] is said to have caused cracks at the surface. Upon inquiry they appeared insignificant as compared with those in anthracite coal mine subsidences and no investigation of them was conducted. Cracks were also reported over lead and zinc mines at Miami, Oklahoma.

A more alarming statement was made by Locke,[89] that

> We have been studying some subsidence in copper and gold mines which involves very much larger movement than any of the examples just cited. The two cases that have been accurately measured show a subsidence of 200 and 350 ft. respectively, at depths between 5,000 and 10,000 ft. The cause was the removal of many million tons of rock during the primary mineralization.

On communication with Dr. Locke, he referred to instances of "mineralization stopping."[90] This, however, is a purely natural phenomenon spread through geological ages, with many consequent interfering factors, and it does not appear that any lesson can be drawn from

[87] S. R. Kay, "The Effect of Subsidence Due to Coal-Workings upon Bridges and Other Structures," *Proc. Inst. Civil Eng. (London)*, Vol. 135 (1899), pp. 114–23.

[88] B. F. Tilson, *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 69 (1923), p. 414.

[89] Augustus Locke, *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 74 (1926), p. 810

[90] Personal communication.

such instances. Other forms of subsidence that can be similarly omitted from consideration are those due to sinking of the surface over limestone caverns ("sink-holes"), for these are seldom more than a few score feet deep.

As opposed to subsidences in regions of tectonic or mineralization disturbances, is the Shandaken Tunnel of New York City's water supply, which between Prattsville (Greene County) and Shandaken (Ulster County), New York, has two stretches of approximately 2 miles each, in which 1,200 feet thickness of Catskill and Chemung shales (the nearest approach that could be found to Bradford type of rocks) overlie the tunnel. There exists also a stretch of 18 miles in which 500 feet of similar rock overlie the tunnel; and there are two stretches of approximately ½ mile each overlain by about 2,000 feet of rock. The tunnel is approximately 15 feet high and the same width. The rock pressure overlying and against the 2,000-foot depth must be approximately 2,250 pounds per square inch throughout the 2 half-mile stretches. The rock pressure overlying and against the 1,200-foot depths of 2 miles each must be approximately 1,350 pounds per square inch under similar assumptions.

Since the rock strata are similar to those of Bradford, the absence of subsidence during construction of the tunnel is an encouraging factor; yet the small size of cross section renders the parallelism negligible, as will be understood after reading the "Theoretical considerations" near the end of this paper.

Comparison of subsidence effects with those due to other causes.— Still further minimizing subsidence due to mining, Rutledge[91] is convinced that it is not as great as that due to other causes. He cites instances of

> certain residences, public buildings, grain elevators and other brick and tile structures in cities, which had been damaged because of foundation settlement, improper drainage, or other reasons having no relation whatever to mining operations.
>
> One cylindrical hollow-tile elevator was cracked at the base from the surface to a height of 5 ft. . . . The top of the elevator, about 90 ft. above the surface, was visibly out of plumb. . . .
>
> . . . .
>
> A certain public building, erected at least 70 years ago, of brick construction, four stories in height, was critically examined. This building rested on a limestone ledge, except at one corner, where an old sewer ran close to the foundation; the walls at this point had settled and a crack had extended about two-thirds of the way up the height of the wall from the ground. . . .
>
> . . . .
>
> At another old brick one-story building used as a brewery, a brick chim-

[91] J. J. Rutledge, *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 69 (1923), pp. 406–13.

ney 30 ft. in height was very much out of plumb. . . . An investigation developed that the walls had separated, horizontally, at a crack, for a distance of $3\frac{1}{2}$ inches. . . .

Small residences of brick and stucco construction were inspected when cracks appeared in the outside walls and the verandah floors began to sink. Several of these buildings were damaged seriously; in fact, more than the brick buildings studied which overlay longwall mine workings.

The writer is informed that when the Boston Transit Commission was constructing the Washington Street Subway, the Ames Building (184 feet high) subsided about half an inch, visibly inclining to one side, due to the lowering of the ground-water level and consequent drying of underground clays. When the water level was restored, however, the building returned approximately to its original position. Reference has already been made to the lowering of certain coasts of the United States, due to normal sinking of the land during historic time, and earthquakes have caused serious depressions of the surface in California, Arkansas and New Zealand. Subsidence is, therefore, due to many causes besides weight of overlying strata. Conversely pressure exerted upwards from a sand need not displace or disrupt the rock column if the materials are firmly fixed laterally and sufficiently strong.

As a commentary on the parallelism assumed between subsidence and upward pressure, it is necessary to explain that the cracking which produces subsidence in the case of mining is due to tension caused by the weight of beds overlying a coal seam and to beam effect due to the breadth of rock. When reservoir pressure acts upward against the weight of the overlying rock, however, it exerts a state of pressure, *not* tension, until very close to the surface. Consequently in the case of reservoir pressure, the following safety factors exist that are not present in a mine.

1. There is a minimum of tension.
2. There is no adjoining support (as a "block" of unmined coal) to constitute a pressure differential.
3. Such differential as exists in the sand reservoir is a decrease of pressure from intake water wells toward the center of each "five-spot" or "seven-spot" (and later outward from the entire property) rather than any sharp change in rigidity laterally.

THEORETICAL CONSIDERATIONS AND STRUCTURAL RESISTANCE OF OVERLYING ROCK

Principal factors in problem.—The following particulars may be accepted as a basis from which to determine mathematically the strength of the rock column overlying the Bradford sand.

1. Although the United States Bureau of Mines has no figures for specific gravity of Chemung shales, the Bureau states that the specific gravity of shales in general ranges from 2.4–2.8. Paul D. Torrey, consulting geologist of Bradford, Pennsylvania, gives as 2.63[92] the specific gravity of Chemung shale directly above the Bradford sand. After due consideration of these data the specific gravity of the strata intervening between the sand and the surface of the field has been fixed at 2.6, which will be accurate enough to meet the needs of this problem.

2. On this basis a rock column one square inch in cross section and one foot high will weigh 1.13 pounds, as opposed to a fresh-water column of the same length and cross section which will weigh 0.433 pound.

3. The net maximum upward pressure of the sand reservoir[93] against overlying materials at critical points beneath the valleys will equal the intake water pressure plus weight of maximum (1,800 feet) water column, minus weight of minimum (1,400 feet) overburden. For an intake pressure of 4,000 pounds per square inch the maximum net upward pressure[94] will then be 4,000 pounds plus 779 pounds minus 1,582 pounds, or 3,197 pounds—approximately 3,200 pounds per square inch.

4. Although there is always loss of head by friction the investigations of the United States Geological Survey indicate[95] that in capillary spaces this loss is not great over long periods of time; and at Bradford it is doubtful whether friction leads to any determinable loss of head between the intake wells and the center of a "five-spot" or a "seven-spot" water-flooding pattern.

5. Since certain geologists have commented on the compressibility of water-bearing sands,[96] the subject had to be given consideration; but compressibility of materials was found to be so slight as not to affect the present problem.

[92] Personal communication to Petroleum Reclamation Company.

[93] The best existing discussion of the causes and nature of reservoir pressures is by W. B. Heroy, "Rock Pressure," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 12, No. 4 (1928), pp. 355–84.

[94] Assuming the wells in the property to range from 1,400 to 1,800 feet deep.

[95] Frank Leverett, "The Water Resources of Illinois," *U. S. Geol. Survey 17th Ann. Rept.*, Pt. 2 (1896), pp. 805–6, 811.
C. R. Van Hise, "Treatise on Metamorphism," *U. S. Geol. Survey Mon. 47* (1904), p. 587.

[96] Charles Terzaghi, "Principles of Soil Mechanics. Elastic Behavior of Sand and Clay," *Eng. News-Record*, Vol. 95 (1895), p. 742 *et seq.*
A. C. Veatch, "Fluctuations of the Water-Level in Wells, with Special Reference to Long Island, N. Y.," *U. S. Geol. Survey Water-Supply Paper 155* (1905), pp. 62, 63, 65–69, 74, and 75.

6. Rock metamorphism, although having interesting scientific tendencies, was not given attention on account of absence of any obvious bearing on the problem.

Only the first four items are important and these were frequently made use of during the investigation.

Safe pressure inferred from consideration of weight of materials and water column alone.—It has already been pointed out that a certain safe pressure can be inferred on very elementary reasoning. That is, since a fresh-water column one foot in height and one inch square in cross section will weigh 0.433 pound, a rock column of the same shape and size having specific gravity of 2.6 will weigh 1.13 pounds, the maximum height of water column (1,800 feet) from surface to top of Bradford sand will weigh 779 pounds. Opposing that weight, since the localities of greatest net upward pressure will lie in the valley, the minimum weight of overburden will be 1,582 pounds. Then:

TABLE II

	Weight in pounds
1,400 ft. rock column, 1 inch square	1,582
1,800 ft. water column, 1 inch square	779
Net safe maximum artificial (intake) pressure, not considering either frictional resistance to flow or structural resistance of overlying rock strata	803

It is clear, of course, that the pressure at which water exists in the sand will not be identical with the sum total of intake and water-column pressures, for reservoir pressure at the bottom of the hole will tend to be dispersed through the interstices owing to the great breadth of the sand. Yet, with passage of time and addition of more water under higher pressures, the unfilled interstices will gradually be thoroughly saturated; hence some compressibility is possible between the theoretical and the actual reservoir pressures. After the interstices are completely filled, no more water can be added under any pressure without tending to lift the roof of the sand under the weak or valley

H. C. Sorby, "On the Application of Quantitative Methods to the Study of the Structure and History of Rocks," *Quart. Jour. Geol. Soc. London*, Vol. 64 (1908), p. 214.

O. E. Meinzer and H. A. Hard, "The Artesian-Water Supply of the Dakota Sandstone in North Dakota, with Special Reference to the Edgeley Quadrangle," *U. S. Geol. Survey Water Supply Paper 520-E* (1925), pp. 73–95.

W. L. Russell, "The Origin of Artesian Pressure," *Econ. Geol.*, Vol. 23, No. 2 (March–April, 1928), pp. 132–57.

O. E. Meinzer, "Compressibility and Elasticity of Artesian Aquifers," *Econ. Geol.*, Vol. 23, No. 3 (1928), pp. 263–91.

A. M. Piper, "Discussion of Paper by W. L. Russell," *Econ. Geol.*, Vol. 23, No. 6 (1928), pp. 683–96.

Charles Terzaghi, "Discussion of Paper by W. L. Russell," *Econ. Geol.*, Vol. 24, No. 1 (1929), pp. 94–100.

W. L. Russell, *ibid.*, Vol. 24, No. 3 (1929), pp. 542–54.

spots (along lines of minimum or 1,400 feet[97] of overlying strata) or cause shearing or other phenomena.

Up to the time when the sand becomes saturated we need not greatly concern ourselves with an excess of pressure; but from that time onward it is imperative to know the maximum artificial or "intake" pressure that may safely be applied without injury to the overlying rock. We are not concerned here with seepage by way of old wells, for these are permanently sealed as fast as necessary. We must and can, however, allow a factor for strength of overlying materials.

Structural resistance of overlying rock.—Since it has already been shown that neither known gas blow-outs, known subsidences or actual measurable pressures in known oil, gas, or water sands afford a positive and final answer to the problem, recourse is necessary to the question of strength of the materials that constitute the 1,400–1,800 feet (more or less) of rock overlying the Bradford sand. It is a surprising fact that mining engineers and geologists have seldom attacked their problems in this way, for it is clear that where solid strata constitute the upper crust of the earth, they form a structure just as truly as a steel plate, artificial concrete floor, or stone arch.

The first attempt, so far as the writer knows, to apply mathematical principles of the mechanics of structures to problems of earth mechanics was a recent article by Clark.[98] He states (p. 54) that

> The strata involved in incompetent folding are analogous to the uniformly loaded beams of structural engineering, and the stresses developed can be analyzed by the methods of that profession.

Although the cantilever effect that he emphasizes will not prevail in the Bradford problem, owing to application of the net pressure from below rather than from above, his article is helpful. He adds (p. 55) that

> It is impossible to compute the actual stresses in a particular fold because the loading cannot be known. But it is possible to set up a hypothetical case in which the stresses can be computed and from it obtain a fair idea of what has happened.

Definitions.—Some of the physical properties of rock are compressive strength, shearing strength, tensile strength, bending strength, hardness, elasticity, and density. A few definitions will be pardonable in order to obviate misunderstanding of what is intended by the use

[97] Assuming the wells to range from 1,400 to 1,800 feet deep.

[98] Stuart K. Clark, "The Mechanics of the Plains-Type of Folds of the Mid-Continent Area," *Jour. Geol.*, Vol. 40, No. 1 (January, 1932), pp. 46–61.

of certain engineering terms. A *stress* is the intensity of internal force called into play by the application of external force. When there is a push, compression results; when there is a pull, tension results; that is, there is a *tensile* stress. A *shearing* force is one acting tangentially instead of at right angles to the surfaces.

A *unit* stress is the stress on a unit of section area. Bending strength is the stress that the materials can sustain without rupture during bending. *Ultimate* strength is the highest unit stress that a material can sustain without rupture (in tension this is from 2 to 4 times the "elastic limit"). Generally, though not universally, ultimate strength is higher in compression than in tension. Thus, according to Merriman,[99] the *ultimate tensile strength* of cast iron is about 20,000 pounds per square inch, whereas its *ultimate compressive strength* is about 90,000 pounds per square inch.

Critical pressure in the present problem is the artificially induced pressure beyond which it will not be safe to raise pressure in the intake wells. It is important to bear in mind that pressure "load" in the Bradford problem is practically a *static or "dead" load* only and will have less effect than a *moving or "live" load* which would cause stresses and strains beyond the static values.

Compressibility of materials.—Table III shows values for the bending strength ("modulus of rupture") and compressive strength of certain rocks under "load" or stress (Marks).[100]

TABLE III

STRENGTH OF ROCKS UNDER "LOAD"

Kind of Rock	*Specific Gravity*	*Compressive Strength (Pounds per Square Inch)*	*Bending Strength*
Trap	2.96	20,000	....
Granite	2.67	19,400	1,850
Slate	2.77	14,000	7,700
Marble	2.72	12,700	1,400
Limestone	2.53	9,500	1,400
Sandstone	2.22	9,300	1,400
Limestone (oölitic)	2.48	6,700	.....

Although these values might suit our purpose, something better was desired, and, after considerable search, a series of results of compressive tests was found on 4-inch cubes of well known rocks. These figures, together with descriptions of the tests and methods used, are

[99] Mansfield Merriman, *Mechanics of Materials* (New York, 1914), 524 pp. (p. 3).

[100] L. S. Marks, *Mechanical Engineers' Handbook*, First ed. (New York, 1916), p. 385.

contained in several reports of the Watertown Arsenal.[101] Table IV shows the values of ultimate compressive strength from this source for comparison.

TABLE IV

COMPRESSIVE STRENGTH OF ROCKS

Kind of Rock	*Applied "Load" (Pounds per Square Inch)*
Cape Ann (Mass.) granite	24,196
Tuckahoe, (N.Y.) marble	11,640 to 19,223*
Vermont marble	9,000
Monson (Maine) slate	8,313
Portland red sandstone	6,173
Ohio sandstone	5,834
Bedford (Indiana) limestone	5,000

* Three tests.

The compressibility of minerals and rocks has also been studied by the Geophysical Laboratory in Washington[102] but only as regards small hand specimens.

Compressive shearing and bending strengths.—In the case of a rock column under pressure from below, however, there are other stresses besides compression. Table V shows strengths under various types of stresses as given in the International Critical Tables.[103]

TABLE V

COMPARATIVE STRENGTH OF ROCKS UNDER TWO TYPES OF STRESSES

Kind of Rock	*Compressive Strength (Pounds per Square Inch)*
Slate, from Pen Argyl, Pennsylvania	9,940
Oölitic limestone from Bedford, Indiana	5,680
	Shearing Strength (Pounds per Square Inch)
Calcareous mica slate from Pen Argyl, Pennsylvania	3,550
Triassic sandstone from East Longmeadow, Massachusetts	2,698
Oölitic limestone from Bedford, Indiana	2,272
Siliceous mica-slate from Monson, Maine	2,130
Argillaceous sandstone from Bavaria	426

In addition Table VI gives the figures for bending strength ("modulus of rupture") from Merriman.[104]

[101] U. S. Arsenal at Watertown, Massachusetts, *Report of the Tests of Metals and Other Materials for Industrial Purposes Made with the United States Testing Machine at Watertown Arsenal, Massachusetts, During the Fiscal Years Ending June 30th, 1890, 1894, and 1895* (Washington, 1891, 1895, and 1896).

[102] L. H. Adams and E. D. Williamson, "On the Compressibility of Minerals and Rocks at High Pressures," *Jour. Franklin Inst.*, Vol. 195 (1923), pp. 475–530.

[103] Published by National Research Council, Vol. 2 (1927), p. 47 *et seq.*

[104] Mansfield Merriman, *American Civil Engineers' Pocket Book*, 3d ed. (New York, 1916), pp. 304 and 357.

TABLE VI

BENDING STRENGTH OF ROCKS UNDER LOAD

Kind of Rock	*Applied "Load"* (*Pounds per Square Inch*)
"Stone" (p. 304)	2,000
Sandstone (p. 357)	1,200
Limestone (p. 357)	1,200
Slate (p. 357)	8,500

The same writer[105] makes the following remarks on strength of various rocks.

The values given in the table for sandstone apply more generally to the ferruginous sandstones, of which brownstone is a common example. The siliceous sandstones, of which the Potsdam variety is the most notable, are more compact and harder to work, but make excellent building stone. Potsdam sandstone has properties of strength approaching those of a good granite. Kidder gives 18,000 to 42,000 lb. per sq. in. as the crushing strength of red sandstone from Potsdam, N.Y. The *Technology Quarterly* for June, 1904, reports 10,655 as the crushing strength of brownstone from Portland, Conn., as shown by a lengthwise test on a block 12 by 6 by 4 inches. For smaller nearly cubical blocks the crushing strength was from 13,000 to 15,000 lb. per sq. in. The same report gives 1576 lb. per sq. in. as the modulus of rupture, 1392 lb. per sq. in. as the shearing strength . . . of Portland brownstone . . . Merrill gives 6950 lb. per sq. in. as the compressive strength . . . of a two-inch cube of sandstone from Middletown, Conn., and for a specimen from Belleville, N.J., he gives 11,700 as the compressive strength. . . . The Arsenal test for 1895 give for the modulus of rupture of sandstone from Longmeadow, Mass., values ranging from 655 to 1273 lb. per sq. in. . . . For two specimens from Cromwell, Conn., the same report gives 1,500 to 2,243 for the modulus of rupture.

Unfortunately there seems to be no record of tests on all of these kinds of strengths in the cases of identical rocks.

Formula for uniform pressure against one side of circular plate.—In considering various methods of estimating the critical pressure, several attempts were made with indifferent success but with the discovery that a number of possible results exist, each one susceptible of reasonable acceptance. Finally the writer decided to use the safe pressure (the 803 pounds stated in Table II) and add to it a more or less arbitrary figure to represent the strength of materials that make up the rock column.

For purposes of determination, let us consider the rock mass overlying the reservoir pressure as being a circular plate, since the rock is not in reality an arch or a cantilever—it is a circular plate fixed around

[105] Merriman, *ibid.*, pp. 357–58.

its edges. The direct way to arrive at the result appears to be to adopt the formula used by structural engineers in the case of circular plates under uniform stresses. Since, in the Bradford field, the strata along the edges of the productive area are held substantially in place by reason of the continuity of the strata and of the arch effect, we may use the formula that pertains to a circular plate of which the circumference is held firmly in place. Speaking of a plate of this sort, Merriman writes[106] that

> Fixing the circumference increases the strength of the plate, for the same reason that the strength of a beam is increased by fixing its ends, and a fixed plate can carry a load about fifty percent greater than that carried by an unsupported one.

The unit stress that a circular plate can carry varies as the square of the thickness and inversely as the square of the diameter, and (according to Kent[107] who quotes Grashof) for circular plates *fixed at the edges* and *under uniform pressure on one side*, the formula is

$$p = \frac{3}{2}\frac{ft.^2}{r^2}$$

where p = uniform pressure or "load" in pounds per square inch
f = the "working stress" (in pounds per square inch) which the rock can sustain
r = the radius of the plate in inches
t = thickness of the plate in inches

Application to Bradford field.—Notwithstanding the care necessary to avoid making false assumptions, it is evident that some may creep into the determination. The formations in reality do not constitute a single plate, but a series of plates superimposed one upon another, each stratum having specific gravity, elasticity, hardness, tensile strength, and ultimate compressive strength differing from those of every other stratum. The relationships between the tensile and compressive strengths are different even within the same stratum. In fact there may be more points of mechanical difference than of similarity. Nevertheless, despite the imperfections that may exist in earth structure, the foregoing formula for artificial structures makes possible a better result than none at all.

In studying the types of rocks of which the National Research Council gives the strengths, one notices that Pen Argyl slate and Berea "grit" (sand)—two extremes of sedimentary rocks—offer the

[106] Mansfield Merriman, *Mechanics of Materials* (New York, 1914), 524 pp. (p. 413).

[107] William Kent, *Kent's Mechanical Engineers' Handbook*, Tenth Edition (New York, 1923), 2247 pp. (p. 374).

nearest approaches to average Bradford materials, although neither of these rocks is identical with any Bradford stratum. The first is similar to hard shale, the second is firmly consolidated sandstone. Table V shows that the compressive strength of the particular slate is 9,940 pounds per square inch and its shearing strength 3,550 pounds per square inch.

The point may be justly raised that, unlike the Chemung and Cattaraugus shales at Bradford, Pen Argyl slate is a metamorphic product; but a study of the Bradford rock section reveals quite a proportion of sandy shales not greatly unlike the "slates." Furthermore, observations at Salt Creek and Teapot Dome, Wyoming, where much faulting was produced during doming of the strata, show that nearly all the transverse faults (those extending across the domal or anticlinal axis rather than parallel to it) exist in the sandstones but practically die out in the adjoining shales. The "habit" of shales is to distribute any tension through a considerable thickness of rock, so that the stress is "taken up" instead of causing fractures, as in the (more competent) sandstones. There is plenty of evidence of this in the Wyoming domes.

Studying the values in Table III and Table VI in connection with the relative proportions of sandstone and shale (10 per cent of the first and 90 per cent of the second), we get *weighted* averages (from the respective tables) of 7,070 pounds and 7,770 pounds per square inch as the bending strength of the rock. However, a more conservative figure is found by the *arithmetical* average, or 4,550 and 4,850 pounds per square inch for the respective tables.

Now, adopting approximately the minimum figure, or 4,500 pounds, we have, in the formula for a circular plate one mile in diameter having a minimum thickness[108] of 1,400 feet,

$$p=\frac{3\times 4{,}500\ (1{,}400\times 12)^2}{2\times(2{,}640\times 12)^2}=\text{approximately } 1{,}900$$

It would appear from this discussion that 1,900 pounds per square inch is a safe figure representing the strength of materials that may be added to the net pressure figure (800 pounds) used in Table II, thereby raising the aggregate safe intake pressure to approximately 2,700 pounds per square inch.

Alternative analysis on basis of assumed failure of overlying rock by shearing.—As opposed to the possibility of the *bending* of the strata, some engineers consider it necessary to recognize *shearing*, owing to a

[108] Naturally the greatest source of danger from any excess of reservoir pressure will be beneath the valleys, but the stresses existing there will be due to the intake water column on the hills; hence the logic of the figure used.

"punching effect" analogous to the resistance encountered when punching a hole in a steel plate. If the plate were lifted by being sheared out of the surrounding rock, the shearing strength along the periphery would have to be overcome. Using a shearing strength of 3,500 pounds per square inch (see Table V), the pressure which could be sustained is said to be 3,700 pounds per square inch; but this maximum estimate can not be accepted without further research.

The earth plate at Bradford is so thick compared with its radius that it is difficult to conceive of any lifting unless the shearing resistance is first overcome. Therefore, if failure of the rock column should take place, it might be by "punching shear" rather than the kind of failure contemplated by the circular plate formula. Should resistance to "punching shear" thus constitute the critical condition, it would follow that the total safe upward (reservoir) pressure would be roughly the above figure plus the net resistance due to weight of the rock column. That is, the critical pressure would be approximately 4,500 pounds per square inch.[109] Neither mining experience, oil and gas experience, nor engineering practice renders plausible the consideration of a higher artificial pressure.

Factors that may influence results.—The results obtained in the foregoing paragraphs carry the assumption that the effects of pressure on water artificially placed in the Bradford sand will not extend outside the one-mile breadth of the Petroleum Reclamation Company's property which it is proposed to flood under high pressure. Any extension of water pressuring across the entire field would modify the results here determined. In a very practical sense, the gradual decrease that will take place in reservoir pressure outward from the company's property will constitute a safety factor that did not exist in mine subsidences, for the sharp lateral change from state of solidity to open cavity at the edge of coal mines does not prevail in the oil fields. On the other hand, pressure will decrease gradually outside the property unless all adjoining properties be water-flooded also.

The use of the formulas for strength of materials presupposes active resistance in the overlying rocks. However, as has been intimated before, if any one of the old wells drilled to the Bradford sand be susceptible to being forced open by a lesser pressure (that is, if the well be imperfectly closed) or if potentially open faults or crevices[110] exist, a study of the strength of materials would be of little avail, for

[109] To which should be added the 800 pounds per square inch net pressure figure given in Table II.

[110] Some geologists maintain that no rocks, however compact and deeply buried even in unfaulted regions, are absolutely devoid of such crevices; but this is a debatable question.

oil or water might ultimately reach the surface of the earth, as is the case with salt, gypsum, and plastic clay in the Gulf coast and elsewhere.

If the flooding be spread over a breadth of a mile, even the cap rock would hardly be broken by the introduction of (say) 8,000 barrels of water into any acre of the field, for the arching would be so gentle as to allot less than half an inch for lifting of the strata in any "seven-spot."

It may also be evident that, although instances of gas blow-outs were cited earlier in the report and then discarded as not pertinent on account of the unconsolidated nature of the strata, water could not cause similar blow-outs, for water or oil pressure would be relieved immediately by an almost negligible lifting of the roof, giving thereby more space for the liquid.

It might seem that the duplication of strata of various types and consistencies might cause an effect of additional strength similar to that of a "compo-board." On the contrary, the existence of stratification or bedding surfaces might tend to weaken rather than to strengthen the rock in its resistance to upward bending or "blow-outs."

However, if this circumstance offers a disparaging factor to the estimate, it may be offset by obvious favorable conditions. First, a minimum or "valley" thickness of rock (1,400 feet) has been assumed, whereas the hilltops actually rise about 1,700–1,800 feet above the Bradford sand.

Secondly, it has been assumed that the "circular plate" will be *uniformly* "loaded" on the under side; but it can hardly be "uniformly loaded" on account of local relatively impervious portions of the sand, differences in pressure between corners and center of a "five-spot" or "seven-spot," and differences in pressure between these units and the surrounding unpressured properties. The two favorable factors may more than offset the possibility of composite weakness. Therefore, consideration of modifying influences does *not* tend to diminish the probable safe minimum pressure of 2,700 pounds (1,900 pounds artificial pressure plus 800 pounds weight of water column that may be safely applied).

CONCLUDING STATEMENT

The order in which various phases of the investigations are herein considered was materially modified during progress of the study. The plan followed was, from time to time, to relegate to an earlier position in the outline such subjects as were duly considered and either sub-

sequently dismissed or used as leading to a later phase of the subject. Salt-dome mechanics appear to be important. The lesson from subsidence, although not recognized in the beginning as particularly helpful, produced a variety of data from many countries and types of mine workings and was therefore elaborated in some detail.

An important lesson was derived in the end from study of the probable structural resistance of the overlying rock. In the beginning nothing seemed to be available on this subject and the mathematics of the matter appeared abstruse, but finally a result was worked out which may be highly illuminating. It now appears certain that the application of principles of strength of materials to the condition at Bradford is *not* an unfathomable subject.

After considering numerous oil sands throughout the world, the fact that some of them crop out at an altitude of more than double that of the sand in the well, and the fact that the only blow-outs known occur in areas of soft formations and abnormal conditions that do not prevail at Bradford, leads to the opinion that intake pressure of approximately 3,000 pounds per square inch at Bradford is a safe one. Even if some point of weakness exist in this conclusion, no disaster need be expected from excess of pressure, because slow increase in pressure and uniform application over a long period of time must give ample warning of any water outbreak or surficial change.

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NATURAL GAS DEVELOPMENTS AND POSSIBILITIES EAST OF THE MAIN OIL AND GAS FIELDS OF APPALACHIAN REGION[1]

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ABSTRACT

Since the discovery, during the past several years, of productive gas fields in south-central New York and northern Pennsylvania, interest has been aroused in prospecting for gas in this general region. This commodity is not subject to over-production in the eastern Appalachian and adjacent regions where adequate market facilities are available. A belt of country immediately east of the old developed oil and gas fields of the Appalachian region is believed to possess possibilities for the development of additional natural gas supplies. Gas in paying quantities has been found east of the 63 or 65 carbon-ratio line, which is usually regarded as the limit for the discovery of oil in commercial amounts. Carbon-ratio lines for this eastern belt are shown on a map which has been prepared by using available coal analyses published by the United States Bureau of Mines.

INTRODUCTION

The possibilities for the discovery of natural gas in commercial amounts in the region east of the main developed Appalachian oil and gas fields—that is, the region extending from south-central New York southwestward to southwest Virginia and thence to Tennessee and Alabama—are attracting interest not only because of the favorable geologic conditions, but also because of near-by markets. This region passes southward from New York through Bradford, southern Tioga, and Sullivan counties, Pennsylvania; then southwestward through Lycoming, Clinton, Clearfield, Cambria, and Somerset counties in that state, to Garrett County, Maryland; next southwestward in West Virginia through Preston, Tucker, and Grant counties to Summers, Mercer, and McDowell counties, thence into Buchanan, Dickenson, Wise, Scott, and Lee counties, Virginia, and adjacent parts of Kentucky and Tennessee. It is a region in which commercially important oil pools will probably not be found, but in which gas pools may perhaps be developed if favorable underground structure is located and adequately tested. Interest in gas prospects in this region has been particularly aroused since the discovery and development in

[1] Published by permission of the director of the United States Geological Survey. Manuscript received, March 6, 1935. Read by title before the Association at the Wichita meeting, March 21–23, 1935.

[2] United States Geological Survey.

1930 of gas in paying quantities in the Oriskany in Schuyler County, New York, and Tioga County, Pennsylvania; in the Hebron field in Potter County, Pennsylvania, in 1931; and has also been stimulated by the bringing in of small amounts of gas in several wells in Somerset County, Pennsylvania, and in counties in southeastern West Virginia.

At this period of much-discussed overproduction and waste of oil, with consequent curtailment in drilling and producing operations, the natural gas industry enjoys a promising outlook for the future, especially on account of the rapid growth during the past few years of interstate transportation of natural gas and the importance of natural gas supplies for cities in industrial regions. In general in the eastern States gas is not subject to overproduction, except perhaps locally and temporarily, because known available supplies are small in relation to the uses served. Nevertheless, enormous quantities of gas have been and are wasted in drilling for oil, especially in regions that lack adequate pipe-line facilities and markets for the gas. The region here under consideration does not, however, lack markets, and additional pipe lines undoubtedly will be constructed if the need arises.

In a report of the United States Bureau of Mines, it was stated that the total natural gas production in the United States during 1930 amounted to 1,943,421 million cubic feet, an increase of 25,728 million cubic feet, or 1.3 per cent over that of 1929. The total consumption of natural gas, computed by deducting exports to Canada and Mexico from the total of production and imports, amounted in 1930 to 1,941,644 million cubic feet, of which 80 per cent was consumed for industrial purposes and 20 per cent was utilized by domestic and commercial consumers. These figures show a slight increase in relative importance of domestic consumption over 1929. In 1933 the marketed production of natural gas was, according to the Bureau of Mines, 1,554,474 million cubic feet, with an aggregate value at points of consumption of about $368,540,000. This was a slight decline from the output of gas in 1932, but this decline was considerably less than the percentage decline for 1932 and 1931 and so indicates some recovery of the natural gas industry in 1933, primarily due to increased consumption for industrial purposes.

The sales value of natural gas at the wellhead or field compressor plant varies from less than 5 cents per thousand cubic feet, where large quantities of gas are available for transport to consuming centers, to 30 cents or more per thousand cubic feet in certain Appalachian fields and in some other areas where only relatively small volumes of gas are produced and the demand exceeds the supply.

The region here described is located in general east of the 65 and, for the most part (north of southwestern Virginia), east of the 70 carbon-ratio line. That is, it is east of the area in which the Pennsylvanian coals have a fixed carbon percentage of 65 or less. In accordance with the so-called carbon-ratio theory of David White, oil in commercial amounts is found only in a few places in the Appalachian region east of the line along which the coals have 63 or at most 65 per cent of fixed carbon (pure coal basis). But, as stated by Doctor White, a carbon ratio above 63 or 65 does not preclude the occurrence of natural gas in paying quantities. In 1915, he said,[3] referring to the Appalachian region:

It is seen that in general the eastern border of the oil field falls near the 60 per cent fixed carbon line, though small pools appear to have been found near the 65 per cent line. Gas pools fringe the oil field in a zone of higher alteration, but no pool of commercial size appears to have been found anywhere in the Appalachian Trough so far east as the 70 per cent line. In fact, it appears probable that a revision of the isovol lines, based on more complete data, will show no pools of oil in rocks of higher carbonization than 65 per cent fixed carbon. . . .

In regions where the progressive devolatilization of the organic deposits in any formation has passed a certain point, marked in most provinces by 65 to 70 per cent of fixed carbon (pure coal basis) in the associated or overlying coals, commercial oil pools are not present in that formation nor in any other formation *normally* underlying it, *though commercial gas pools may occur in a border zone* of higher carbonization.

In several more recent papers[4] similar statements have been made by Doctor White, and his theory has been amply supported by thousands of applications of it throughout this country and others.

It should be borne in mind that in areas of higher degrees of carbonization, the deeper formations, that might otherwise offer some promise as gas reservoirs, may have been, at least locally, too much cemented to be now capable of retention of large gas supplies.

If a recalculated analysis is not available, the carbon ratio of any local coal can be ascertained by dividing the fixed carbon of the proximate analysis (sample as received) by the sum of the fixed carbon and volatile matter which gives the percentage of fixed carbon on a pure coal basis.

[3] David White, "Some Relations in Origin Between Coal and Petroleum," *Washington Acad. Sci. Jour.*, Vol. 5, No. 6 (March 19, 1915).

[4] David White, "Genetic Problems Affecting Search for New Oil Regions," *Min. & Met.*, No. 158 (February, 1920); "Progressive Regional Metamorphism of Coals," *A.I.M.E.*, No. 14141 (February, 1925); "Geology and Occurrence of Petroleum in the United States," Secs. 1 to 7, H. Res. 441, Pt. 2, Hearings Before a Subcommittee of the Committee on Interstate and Foreign Commerce, House of Representatives, 73d Cong. (Recess) (1934); "Effects of Geophysical Factors on the Evolution of Oil and Coal," *Jour. Inst. Petrol. Tech.* (London) Vol. 21, No. 138 (April, 1935), pp. 301–10.

The accompanying map (Fig. 1), showing the Appalachian oil and gas fields, also shows carbon-ratio lines (isocarbs) from about 60 per cent to approximately 80 per cent fixed carbon. The percentages of fixed carbon for plotting the lines were compiled with the use, so far as available, of composite analyses published by the United States Bureau of Mines of coals from the various states, but not always from the same bed of coal. All the analyses that were used were made of samples from coal beds of Pennsylvanian age and, wherever possible, analyses of the Lower Kittanning bed were used (Fig. 1). Lines have been drawn solid where coal analyses were available for computing fixed-carbon percentages, and dashed where hypothetical.

AREAS EAST OF MAIN OIL AND GAS FIELDS IN WHICH GAS HAS BEEN DEVELOPED OR PROSPECTING FOR GAS HAS BEEN DONE

PENNSYLVANIA

Most of the oil and gas sands of Pennsylvania which are shown in Table I are, according to S. H. Cathcart,[5] stratigraphically well below most of the coal beds, and the determination of the degree of carbonization of the deeper sands requires consideration of the "unconformity at the base of the Pottsville and of the effect of probable recurring deformation below that unconformity."

East of the main oil and gas fields in Pennsylvania there are known to be a number of structural domes and anticlines that are favorable for prospecting for gas. It is probable that the irregularities of accumulation that exist in the "shallow" sands of Pennsylvania will not apply to the same extent to the accumulation of gas in the Oriskany. The Oriskany, it is hoped, will prove in some areas to be more continuous than most of the shallow sands.

As will be noted from the accompanying isocarb map of Pennsylvania[6] (Fig. 2), there are, in the region under discussion, "islands" or local areas in which the percentages of fixed carbon in the coals do not agree with the adjacent isocarbs.

Tioga County.—In September, 1930, a well drilled by the Allegheny Gas Company on the Sabinsville anticline in Tioga County yielded 22 million cubic feet of gas per day at 1,665 pounds pressure at a depth of 4,006 feet from the Oriskany sand (Devonian). This formation has a thickness in Tioga County varying from 17 to 69 feet.

[5] S. H. Cathcart, "Geologic Structure in the Plateaus Region of Northern Pennsylvania and Its Relation to the Occurrence of Gas in the Oriskany Sand," *Pennsylvania Top. and Geol. Survey Bull. 108* (March, 1934).

[6] G. H. Ashley, "Bituminous Coal Fields of Pennsylvania," *Pennsylvania Top. and Geol. Survey Bull. M-6*, Pt. 1 (1928), p. 165.

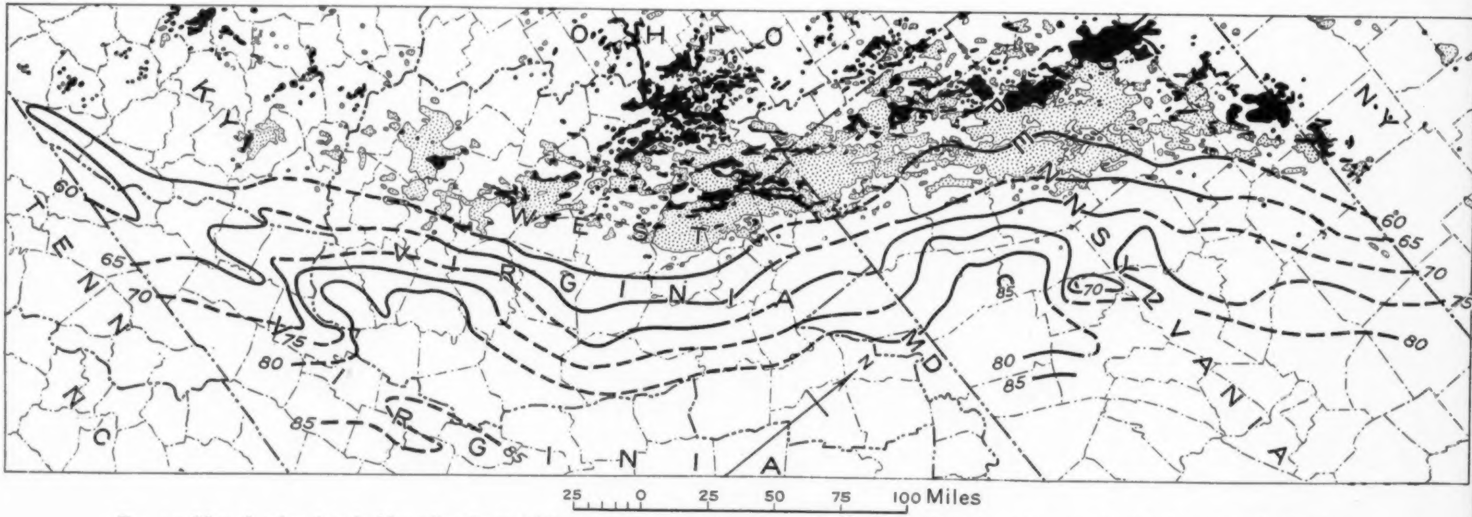

FIG. 1.—Map showing Appalachian oil and gas fields and carbon-ratio lines (isocarbs) from about 60 per cent to approximately 80 per cent fixed carbon.

TABLE I

PRINCIPAL OIL AND GAS SANDS AND MARKER HORIZONS OF PENNSYLVANIA
(After Geo. H. Ashley and J. D. Sisler, *Pennsylvania Top. and Geol. Survey Bull. M-19*, 1933, p. 6.)

Systems	*Series*	*Groups*	*Geologic Names of Outcropping Beds*	*Driller's Names (Correlation below Big Injun and Berea tentative) First name most widely used*	*Intervals*		
					South-western	*Central*	*Northern*
Pennsylvanian	Pittsburgh	Monongahela	Pittsburgh coal	Pittsburgh coal	0		
		Conemaugh	Morgantown sandstone	Murphy sand	140		
			Saltsburg sandstone	Little Dunkard, Cow Run sand	310	700	
			Mahoning sandstone	Big Dunkard, Hurryup sand	515	530	
		Allegheny	Upper Freeport coal	Upper Freeport or Connellsville coal	625	430	
			Freeport sandstone	Upper Gas or Second Cow Run sand	670	390	
			Kittanning sandstone	Middle Gas sand			
			Vanport limestone	Ferriferous limestone		200	
			Clarion sandstone	Lower Gas sand	825	190	
	Pottsville	Beaver River	Homewood sandstone	First Salt sand	915	130	
			Connoquenessing sandstone	Second Salt sand	1,000	60	530
			Sharon (Olean) sandstone	Third Salt sand, Maxton sand			430
Mississippian	Chester	Mauch Chunk	Greenbriar limestone	Little lime, Salvation sand	1,100		
			Red shale	Pencil cave	1,120		
	Meremec	Ste. Genevieve	Loyalhanna limestone	Big lime, Mountain limestone	1,150		
	Waverly (Pocono)	Burgoon	Burgoon sandstone	Big Injun or Mountain sand	1,200	0	
			Shenango sandstone				380
		Cuyahoga	Meadville (Patton)	Red shale	1,550	300	
			Sharpsville sandstone	Squaw sand	1,600		290
			Sunbury (Orangeville)	Papoose sand	1,715		
		Berea	Berea (Corry) sandstone	Berea and Murrysville, Butler-thirty-foot, Second Gas	1,775	550	150

Systems	Series	Groups	Geologic Names of Outcropping Beds	Driller's Names (Correlation below Big Injun and Berea tentative) First name most widely used	Intervals South-western	Central	Northern
Devonian	Upper Devonian	"Catskill"	Cussewago sandstone	Hundred-foot, Fifty-foot, and Gantz First sand of Venango County	1,875	750	0
			Riceville shale	Thirty-foot, Nineveh thirty-foot	1,980	850	
			Woodcock sandstone	Snee, Blue Monday, Boulder, Hickory	2,045	925	140
			Saegertown shale	Gordon stray, Third stray, Campbell Run sand,	2,080		
				Second sand Venango County	2,150	1,040	280
			Miller or Salamanca sandstone	Gordon, Third sand of Venango County	2,200	1,100	380
			Amity shale	Fourth sand			
			Le Boeuf or Panama sandstone	Fifth McDonald sand	2,270	1,200	460
		Chemung	Chadakoin shale and flaggy sandstone	Sixth, Bayard sand	2,350	1,300	580
				Elizabeth sand	2,475	1,430	730
				Warren First sand (local)	2,710	1,580	850
			Girard shale	Warren Second sand (local)	2,810	1,700	930
				Warren Third sand	2,900		1,000
			Cuba sandstone (?)	Speechley stray	3,000	1,900	
				Speechley, Glade	3,125	2,010	1,075
				Tiona, Clarendon	3,250	2,200	1,200
			Northeast shale, etc.	Balltown, Gartland, Cherry Grove sands	3,360	2,300	1,280
				Second Balltown, Chipmunk Sheffield, Cooper (?) sand	3,510		1,570
			Shumla sandstone	First Bradford sand	3,620		
			Westfield shale	Second Bradford sand	3,700		
			Leona sandstone	Third Bradford, Deer Lick sand	3,800	2,700	1,715
				Smethport, Kane, Elk groups	3,900	2,850	
	L. Dev.		Oriskany sandstone	Oriskany	6,530	5,550	5,000
Silurian	Lower Silurian	Medina	Tuscarora sandstone	Medina sand, Clinton sand of Ohio (est.)	8,300	6,750	6,100

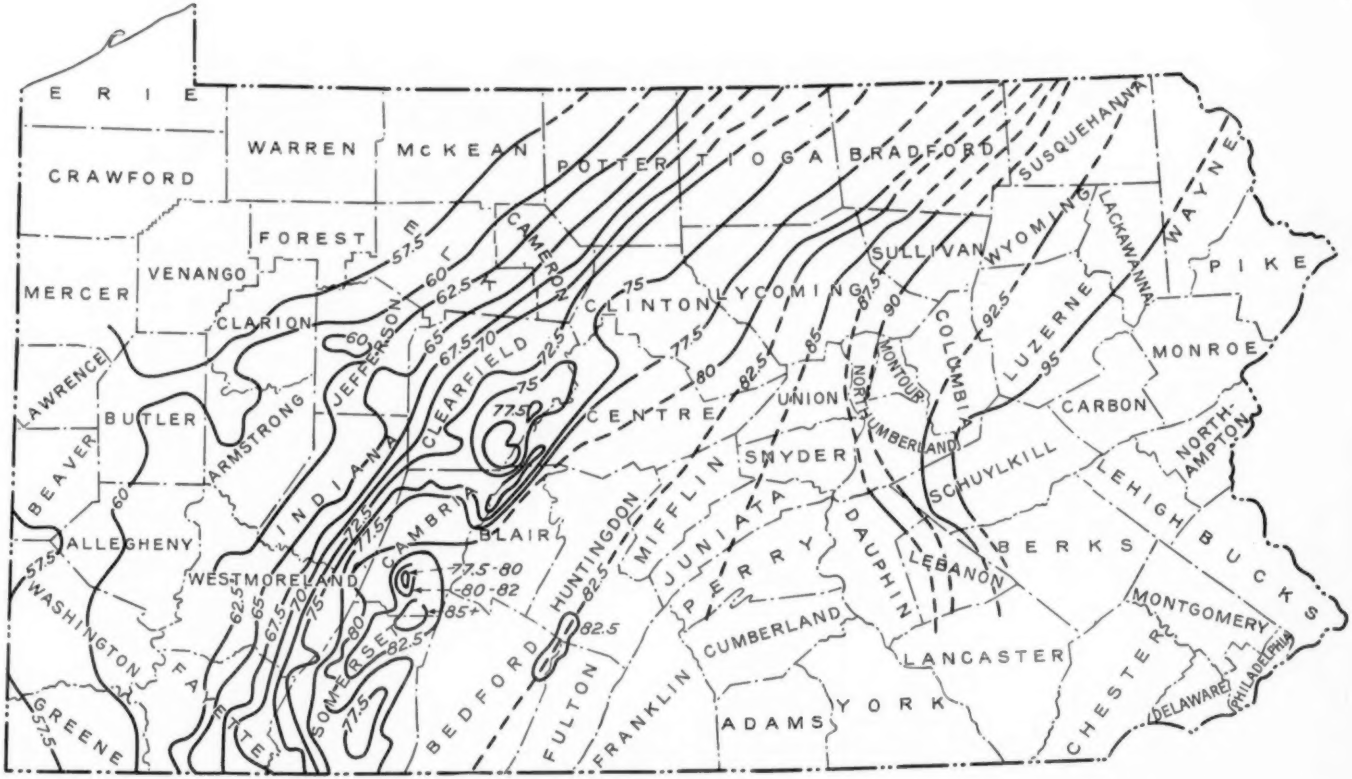

FIG. 2.—Isocarb map of Pennsylvania, showing increase in percentage of fixed carbon in coal from west to east. After George H. Ashley, *Pennsylvania Top. and Geol. Survey Bull. M-6*, Pt. 1 (1928), p. 165.

The following statement concerning gas developments in Tioga County has been made by the State Survey.[7]

> During the three years since discovery of the Tioga field 101 locations have been active in Tioga County. . . . 92 wells have reached the Oriskany, 43 are producers, 49 are dry holes, and 6 have been abandoned above the sand. . . . The initial volume of the successful wells ranges from 85,000 to 70,000,000 cubic feet in 24 hours with rock pressures of 1,460 to 1,675 pounds per square inch. The average initial volume of the wells completed is about 15,000,000 cubic feet and the aggregate volume about 628,500,000 cubic feet a day.

The cost of a well in this field is given as about $18,000.

Gas from the Tioga field is supplied to Syracuse, New York, and to cities in the upper Susquehanna Valley through a pipe line running southward to Williamsport, Pennsylvania. The gas is also furnished to distributors in Corning and Elmira, New York, where natural gas has been substituted for artificial gas.

The Weiboldt well in the southeastern corner of Tioga County is reported to have struck the Oriskany at 5,992 feet and drilled to a total depth of 6,045 feet without production (elevation 1,870 feet).

The carbon ratios in Tioga County range from about 60 or 65 in the northwestern part to over 75 in the southeastern portion.

Potter County.—Another interesting development of natural gas in northern Pennsylvania is in the Hebron field, in Potter County.

Previous to 1931 all of the gas in this county was produced from relatively shallow sands (Upper Devonian) at depths ranging from 750 to 2,400 feet with low pressures. In November, 1931, a gas well was developed in Hebron Township, that produced from the Oriskany at a depth of about 5,000 feet. The discovery well was rated at 8 million cubic feet per day with a rock pressure of 2,100 pounds per square inch. Of eight wells drilled in 1932, in the Hebron field, six found pay in the Oriskany with a total initial production of 81,240,000 cubic feet; in 1933 seven wells out of fifteen proved to be gassers, with a total daily production of 123,371,000 cubic feet, and in 1934 seventeen of twenty-two wells drilled added a production of 277,965,000 cubic feet of gas, making a total of 490,826,000 cubic feet for the field.[8] The average depth of the wells is about 4,885 feet and the rock pressure about 2,000 pounds per square inch. In 10 of the wells drilled in Potter County between 1932 and 1934 the Oriskany was encountered at depths varying from 4,875 feet to 5,875 feet.

[7] S. H. Cathcart and T. H. Myers, "Gas in Tioga County, Pennsylvania," *Pennsylvania Top. and Geol. Survey Bull. 107* (February 1, 1934).

[8] *Oil and Gas Jour.* (November 22, 1934).

A well in the southern part of Potter County on the Marshlands anticline, East Fork district, is reported to have encountered the Oriskany at 6,280 feet (4,344 feet below sea-level), and the Oriskany sand—said to be 31 feet thick—yielded an initial 85,000 cubic feet of gas per day. This well (Emporium Lumber Company) was drilled to a depth of 6,425 feet into the Helderberg limestone. A second well on this anticline reached a depth of 6,023 feet and also yielded a small amount of gas. The Moran well,[9] in northern Potter County on the Smethport anticline, drilled to 4,879 feet, found the Oriskany at 2,788 feet below sea-level, and had an initial open-flow volume of gas of 8 million cubic feet at 1,950 pounds rock pressure.

In 1933 a line connecting the Hebron field to the Farmington-Syracuse gas pipe line was completed. In December, 1934, oil journals reported that a well in Genesee Township encountered 27,250,000 cubic feet of gas at a depth of 5,148 feet and one in Allegany Township had a gas production of 19,750,000 cubic feet at a depth of 5,216 feet.

Carbon ratios in Potter County range from less than 60 per cent in the northwestern part of the county to more than 70 per cent in the southeastern part.

Lycoming County.—Many years ago a small quantity of gas was reported in a well drilled near Ramsey in this county. A well drilled in 1931 and 1932 in Shrewsbury Township reached a depth of 5,080 feet and was dry, but did not, according to reports, penetrate the Oriskany.

In western Lycoming County, where the Hyner anticline ends, the Cogan House anticline begins and extends about 20 miles into the eastern part of the county. The Wilmot anticline extends from northeastern Lycoming County to western Susquehanna County. Tests to the Oriskany, especially in the western part of the county, might result in the discovery of gas.

The carbon ratios vary from about 75 in the western part of Lycoming County to about 90 in the extreme eastern part.

Cameron County.—One small gas field has been developed in this county, on Elk Fork of Driftwood Branch, in the extreme northwestern corner of Shippen Township, a few miles from the McKean-Elk County line. Gas has also been found in small quantities in scattered wells in the county, but the gas discoveries have been in "shallow" sands and not in the Oriskany. The Pennsylvania Survey has described[10] the possibilities for the development of gas in the Oriskany in this county.

[9] S. H. Cathcart, "Gas and Oil in Potter County, Pennsylvania," *Pennsylvania Top. and Geol. Survey Bull. 106* (February 1, 1934).

[10] S. H. Cathcart, "The Possibility of Finding Gas in Cameron County, Pennsylvania," *Pennsylvania Top. and Geol. Survey Bull. 109* (March 15, 1934).

Apparently there is little, if any, available information concerning the distribution, depth, and thickness of the Oriskany in Cameron County, or as to whether, if present in sufficient thickness, it contains gas.

In December, 1934, an item appeared in *The Oil and Gas Journal* to the effect that the Tioga Natural Gas Company's Emporium No. 1 in Shippen Township encountered an immense gas pocket at a depth of 4,715 feet, considerably above the Oriskany. The tools were blown out and the gas pocket lost, but drilling will be continued. This well is on the Shippen dome of the Harrison anticline.

The northwestern part of the county lies between the 60 and 65 carbon-ratio line and the 70 line probably extends through the southeastern corner.

Clinton County.—Several structures that may possess deep gas possibilities are known to exist in Clinton County.[11]

A dome on the Wellsboro anticline occurs in Leidy Township. A shallow gas field (Kettle Creek field), now practically abandoned, was developed on the north flank of the Leidy dome about 1922. The dome appears to center in Leidy Township and to have good closure east and west. The largest of the wells in this field was reported to have a capacity of 2 million cubic feet, with a rock pressure of 960 pounds per square inch, production being from a depth of about 900 feet. This field has been described by the Pennsylvania Survey in its mimeographed Bulletin 78 (1923). The Oriskany has not been tested in this locality, so far as present information is available.

Doming of the Laurel Hill (Hyner) anticline is known to exist in the vicinity of Hyner in Clinton County, and years ago gas was encountered in at least two wells near Hyner at depths between 1,200 feet and 2,000 feet.

Carbon ratios in the county range from more than 70 in the northwest to about 80 in the southeast.

Clearfield County.—During 1930, considerable drilling in this county was reported and at least two wells produced gas with an approximate open flow of 2 million cubic feet each. The production was said to be from the Sheffield sand. There were four producing gas wells in the county in 1931 and sixteen in 1932.

Coals in Clearfield County indicate a carbon ratio ranging from about 67 to more than 75.

Cambria County.—The White Mill Oil & Gas Company's well on Route 422, between Belsano and Strongstown, was reported in 1933

[11] S. H. Cathcart, "Geologic Structure in the Plateaus Region of Northern Pennsylvania and Its Relation to the Occurrence of Gas in the Oriskany Sand," *Pennsylvania Top. and Geol. Survey Bull. 108* (March, 1934).

to have encountered 15,000 cubic feet of gas at a depth of 3,160 feet and in January, 1934, the well was drilling at a depth of 5,000 feet. Nothing more recent is known of this well.

The 75 and 80 carbon-ratio lines extend through this county.

Somerset County.—Since 1929 there has been some activity in prospecting for natural gas in this county. In 1930 a well in Quemahoning Township was drilled in with an open flow of 750,000 cubic feet of gas and rock pressure of 800 pounds. The reported depth was 2,552 feet. In 1932 two wells were drilled in this township, one with a reported initial flow of gas of 1 million cubic feet and the other dry. The depths at which gas has been encountered in this district are between 2,500 and 3,000 feet. The gas wells are near the axis of the Somerset syncline and the gas is from a lens near the middle of the Catskill formation, according to G. B. Richardson.[12]

Coals in Somerset County show a range in carbon ratio from about 71 in the extreme western part to more than 80 in the eastern portion.

Dry tests to Oriskany in Pennsylvania.—Deep tests made during 1932 to the Oriskany in counties in Pennsylvania east of developed oil and gas fields—which proved, however, to be dry holes—included wells in several townships in Bradford County and also in Sandy Township in Clearfield County, in Shrewsbury Township in Lycoming County, in Apolacon Township in Susquehanna County, and in Eaton Township in Wyoming County. The failure to find production may possibly be attributed to the tightness or absence of the Oriskany. Following is a list of five wells drilled in Bradford County which penetrated the Oriskany but encountered no gas.

Columbia Township, Olsen No. 1, elevation 1,865 feet; Oriskany at 5,645 feet; shut down at 5,690 feet

Ulster Township, Kennedy No. 1; elevation 1,445 feet; Oriskany at 5,510 feet; dry hole at 5,530 feet

Wells Township, Braested No. 1, elevation 1,600 feet; Oriskany at 4,729 feet; abandoned at 4,750 feet

Stevens Township, Brown No. 1, elevation 1,260 feet; Oriskany at (not given); abandoned at 6,290 feet

West of Towanda, Hettick No. 1, elevation 1,280 feet; Oriskany 5,163 feet; abandoned at 5,227 feet

NEW YORK

For many years gas has been produced, at least in small amounts, in a number of counties in New York state from Onondaga and Oswego to the counties bordering Lake Erie.

In 1930 (March), the Belmont Quadrangle Drilling Corporation of Bradford, Pennsylvania, brought in a gas well on the Pulver Farm in what is known as the Dundee area. The well was reported to have

[12] G. B. Richardson, *U. S. Geol. Survey Somerset-Windber Folio 224* (1935).

had an initial flow of 6 million cubic feet of gas per day with a rock pressure of more than 700 pounds. The depth of the well was 2,075 feet and the producing formation was identified as the Oriskany sandstone. Drilling of other wells progressed rapidly and after the limits of the Dundee area were partially defined by the drilling of three dry holes in the town of Barrington, at the north, and one in Altay, at the south, exploration proceeded westward and northwestward into Wayne and Barrington Townships, known now as the Wayne area. There are now more than 100 producing wells in the Wayne-Dundee areas. Initial open flows average about 6 million cubic feet per day and rock pressure is about 700–750 pounds.

Since the development of this field there has been active prospecting in several counties, notably Schuyler, Steuben, Yates, Chemung, Allegany, and near-by counties, and it seems probable that additional supplies of gas will be developed at other localities in the Oriskany sand and the Medina and in some places in the Trenton. A moderate quantity of gas was reported in a test well in Cattaraugus County drilled to a depth of 6,250 feet to the Medina. In that part of the State south of Finger Lakes, the Medina ranges from about 1,500 to 1,800 feet below the Oriskany. News items have appeared recently to the effect that an initial gas production of 12,800,000 cubic feet with a rock pressure of 1,900 pounds has been encountered in a well near Greenwood in Steuben County at a depth of 4,256 feet in the Oriskany and in November, 1934, the Wittmer No. 2 well had an estimated daily flow of 35 million cubic feet. In January, 1935, a well in Greenwood Township in Steuben County, the largest gasser so far developed in New York, was brought in with an estimated production of 50 million cubic feet. The top of the Oriskany was encountered at 4,737 feet and the well was completed one foot in the sand. In the same month, a well in the Genesee field of Potter County, Pennsylvania, came in as an 8-million cubic-foot producer in the Oriskany at 4,009 feet.

A well on the H. Dunn Farm at Camden,[13] in Oneida County, has encountered gas with an estimated daily capacity of 17 million cubic feet. This development may lead to the opening of a new field east of any so far developed in the state. Small quantities of gas have been encountered in the Utica shale, Medina, and Trenton in wells drilled in previous years in this county. Another locality of interesting recent gas development is the Clyde district, in Wayne County, where several wells have encountered good flows of gas, the first test coming in with an estimated flow of 3 million cubic feet at a depth of 2,730 feet in the Trenton. Trenton production is also reported from several

[13] *Gas Age Record* (New York City, November 10, 1934).

wells west of Lowville in Lewis County, and the gas is piped to Lowville.

The following summary of gas-producing counties and formations in New York is taken from Circular 7 (February, 1932) of the New York State Museum.

Gas Formations	*Counties of Production*
Chemung and Portage sandstones	Allegany, Cattaraugus, Chautauqua, Steuben
Marcellus shale	Cattaraugus, Erie, Livingston, Ontario, Schuyler
Onondaga limestone	Cattaraugus, Erie
Oriskany sandstone	Schuyler, Steuben, Yates
Salina water lime	Cattaraugus, Erie
Medina sandstone	Cattaraugus, Chautauqua, Erie, Genesee, Livingston, Monroe, Ontario, Wyoming
Trenton limestone	Onondaga, Oswego

To this may now be added Niagara gas production in Ontario County since the discovery of gas wells, producing from the Niagara limestone, was reported in 1932 and 1933. In 1932 two wells in Phelps Township were completed with open-flow capacity of 2,750,000 cubic feet. Oneida County and Lewis County may also be added to those of Trenton gas production.

In the Minerals Yearbook, 1934, of the United States Bureau of Mines, it is stated that tests for gas were made in Montgomery, Oneida, and Lewis counties bordering the Adirondack pre-Cambrian region, but that only small showings resulted. Also that a well in Oneida County penetrated about 375 feet of reported Grenville series at a depth of about 2,420 feet and the driller reported small quantities of gas in the Trenton and in the Grenville. This is of particular interest in connection with the fact that the presence of natural gas in the Grenville series has been previously noted[14] in zinc mines at Edwards in St. Lawrence County.

Paul D. Torrey states[15] that in prospecting for gas in New York, it should be borne in mind that

> gas production from the Oriskany conforms rather closely to closures on anticlinal axes, and that irregularities in Oriskany deposition so govern the accumulation of gas that studies of the deposition and lateral extent of the sandstone are of equal importance to actual structural mapping.

The Oriskany is a highly fossiliferous sandstone outcropping in an east-west direction across New York a little north of the Finger Lakes. Its general dip is toward the south under younger Devonian formations and it is reported to be about 4,000 feet deep at the Pennsylvania boundary.

[14] J. S. Brown, "Natural Gas, Salt, and Gypsum in Pre-Cambrian Rocks at Edwards, New York," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 8 (August, 1932).

[15] *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 6 (June, 1931), p. 688.

In the summer of 1934, the United States Geological Survey field party under the direction of W. H. Bradley conducted investigations of the gas resources of all or parts of Livingston, Allegany, Steuben, Chemung, Schuyler, Yates, Ontario, and Cattaraugus counties as a Public Works project, and the results are being prepared for publication. A preliminary press notice on the Watkins Quadrangle will soon be published by the United States Geological Survey. Additional field work will be done before the complete report will be issued.

MARYLAND

Garrett County.—The Potomac Oil and Gas Corporation drilled a well on the north side of the North Branch of Potomac River, just west of Steyer, the elevation of which was 2,350 feet and the depth 2,240 feet. A showing of oil and a little gas were reported, the oil showing in the Maxton sand of Mississippian age.

Gas may possibly be found in this part of Maryland, if adequate tests are made on favorable local structures.

Carbon ratios in the county range from about 70 in the extreme northwestern part to more than 80 in the eastern portion.

WEST VIRGINIA

Favorable structures exist in several of the counties in West Virginia east of the developed oil and gas fields, and these structures offer some promise for the development of additional gas supplies. In the most important oil and gas fields of the state, production has been generally from formations of Pennsylvanian, Mississippian, and Upper or Middle (?) Devonian age, but in these fields, as well as east of them, deeper sands should be given attention. Recently (February, 1935) a test in the Malden district of Kanawha County, West Virginia, reported the top of the Oriskany at 4,803 feet, and at that depth gauged 750,000 cubic feet of gas (Table II). This later increased to 1,047,000 cubic feet of gas per day with a small amount of oil, and the well was shut in during repairs to the rig before being drilled deeper. Other wells are being drilled in this area to test the Oriskany.

The West Virginia Geological Survey has published detailed county reports, with maps, covering most of the counties in the state, and these reports include discussions of oil and gas possibilities and information as to depths to deep sands. The counties mentioned in the following paragraphs are among those worthy of consideration in the matter of prospecting for gas to be piped for industrial uses.

Mineral and Grant counties.—The West Virginia State report on these counties states that the carbon ratios of the Upper Freeport

coal vary from 77 to 83. Yet some localities in the counties are regarded as possessing gas possibilities; notably the summit of Patterson Creek ridge and the Wills Mountain anticline. Showings of oil and gas have been noted in a few wells in Grant County.

TABLE II

OIL AND GAS HORIZONS OF WEST VIRGINIA

(After D. B. Reger, *West Virginia Geol. Survey County Rept. on Randolph County*, 1931, pp. 400–02.)

PENNSYLVANIAN	
Monongahela series	Carroll sand (Uniontown)
Conemaugh series	Minshall sand (Connellsville)
	Murphy sand (Morgantown)
	Moundsville sand (Saltsburg)
	First Cow Run, or Little Dunkard sand (Buffalo)
	Big Dunkard sand (Mahoning)
Allegheny series	Burning Springs sand (Upper Freeport)
	Gas sand of Marion and Monongalia counties (Lower Freeport)
Pottsville series	Second Cow Run sand of Ohio (Homewood)
	Cairo gas sand
	Cairo salt sand
	Rosedale gas sand (Guyandot)
	Rosedale salt sand (Sharon)
	Breeden sand of Mingo County
MISSISSIPPIAN	
Mauch Chunk (Red shale) series	Princeton sand
	Maxton sand (Droop)
	Little lime (Reynolds? or Glenray?)
Greenbrier (Limestone) series	Big lime
Pocono (Sandstone) series	Keener sand and Beckett sand of Milton
	Big Injun sand (Logan, Burgoon)
	Squaw sand
	Weir sand (Broad Ford)
	Berea sand
DEVONIAN	
Catskill (Red-bed series)	Gantz sand
	Fifty-foot sand
	Thirty-foot sand
	Gordon Stray sand
	Gordon sand
	Fourth sand
	McDonald, or Fifth, sand
	Bayard, or Sixth, sand
Chemung series	Elizabeth, or Seventh, sand (Hendricks)
	Warren First sand
	Warren Second (Burnside?) sand
	Clarendon, or Tiona, sand
	Speechley sand
	Balltown, or Cherry Grove, sand
	Sheffield, or Cooper (Riley?) sand
	Benson, Bradford? or Deer Lick, sand
	Elk, or Waugh and Porter, sand
Portage series	Kane sand
Genesee (Black shale) series	Childress sand of Cabell County
Hamilton (Brown shale) series	Gas in Ohio and Kentucky, and in southern West Virginia
Marcellus (Black shale) series	Gas in Ohio and Kentucky, and in southern West Virginia

Corniferous (Columbus) limestone	Ragland, Menefee, or Irvine, sand of Kentucky	
Oriskany sandstone	Oriskany sand	
Helderberg limestone	Coeymans sand near base	"Big lime" of Ohio
SILURIAN		
Bossardville limestone		"Big lime" of Ohio
Rondout limestone		"Big lime" of Ohio
Niagara limesone	Oil in western Kentucky	"Big lime" of Ohio
White Medina sandstone	"Clinton" sand of Ohio	
ORDOVICIAN		
Martinsburg, or Cincinnati, (Shale) series	Hudson sand group of Kentucky	
Trenton and other limestones, (mostly Martinsburg series)	Trenton sand group of northern Ohio	

Hampshire County.—In 1931 the Maryland Natural Gas Utilities Corporation purchased a well being drilled 3 miles west of Romney by the Hampshire Oil and Gas Company. The drilling was continued to 1,200 feet and according to reports a flow of gas was encountered The well was located on the west slope of the Stratford Ridge anticline. It started in the Marcellus shale and was drilled probably into the Oriskany sandstone or the Helderberg limestone.

This county is considerably east of the 80 carbon-ratio line, and apparently does not offer as much promise for gas in large quantities as adjacent areas on the west.

Tucker County.—One deep well has been drilled[16] in Tucker County at Parsons near the western corner of Hampshire and Hardy counties. Its total depth is reported as 4,250 feet, penetrating 80 feet of Oriskany and going 190 feet deeper. A gas pocket was recorded in the "Corniferous" at 3,830 feet and a little gas was encountered in the Portage.

The crest of the Blackwater anticline in Canaan Valley, as mentioned in the county report[17] by the State Survey, is a favorable locality for prospecting for gas in the Oriskany or "Clinton."

The carbon ratios in the county are 75 or more in the central part of the county where coal analyses were available.

Randolph County.—In 1932 a well, just west of Kerens near Elkins, encountered the Oriskany at 4,200 feet and was drilling in the "Clinton" below 4,300 feet, having struck no oil or gas. No further information concerning this well is in hand.

In a State report[18] on the geology and mineral resources of this county, it is stated that "analyses of 51 samples of Sewell coal in the

[16] J. L. Tilton, W. F. Prouty, R. C. Tucker, and P. H. Price, *West Virginia Geol. Survey County Rept. on Hampshire and Hardy Counties* (1927), p. 367.

[17] D. B. Reger, *West Virginia Geol. Survey County Rept. on Tucker County* (1923), p. 271.

[18] D. B. Reger, *West Virginia Geol. Survey County Rept. on Randolph County* (1931), p. 399.

whole county showed an average carbon ratio of 71" and that "it seems probable that prospecting for gas east of Tygart Valley would be extremely hazardous." The following statement is also quoted from the report.

> The Oriskany sand, which is nearly always coarse and porous and often 100 feet or more in thickness, has considerable possibility for gas in this county but it is very deep in the region west of Tygart Valley. On the Deer Park anticline its depth would not be excessive but the danger of crooked holes, on account of sloping strata, would be considerable.

The White Medina ("Clinton" of Ohio) is probably present in sufficient thickness in Randolph County to offer possibility as a gas reservoir.

Pendleton County.—Probably carbon-ratio lines of 75 and 80 should be extended through this county. Two samples of coal on the side of Roaring Plains indicate a carbon ratio for that locality of 77.

Pocahontas County.—In Pocahontas County, a showing of oil was reported in one deep well and traces of gas reported in a few shallower wells. Just west of this county, in Webster County, 6 deep wells have been drilled and 4 of them encountered small quantities of gas.

Sands in the Pocono and in the underlying Devonian formations in western Pocahontas County are regarded as possibly favorable for testing for gas. The Oriskany is a suitable reservoir, but lies at considerable depth in this area.

In the western part of the county the average carbon ratio of three samples of Sewell coal is given as 73.

Nicholas County.—This county lies west of those with which this paper deals especially. According to the West Virginia Geological Survey report on this county, published in 1921, 22 deep tests in the county gave the following results: 7 were dry, 1 had sufficient oil to have made a producer, 8 were gas wells of sufficient volume to be classed as productive, and 6 had slight showings of oil and gas. Those which yielded production were located along the northern or northwestern border of the county. Of two deep tests south of Gauley River, one encountered a slight showing of oil and the other struck a small amount of gas. At that time no wells had been drilled in the county to the deeper sands which have produced oil or gas in other States. In 1924 six wells in the county were producing 9 million cubic feet of gas from the Mississippian.

Carbon ratios in this county range from 60 in the western part to about 70 in the eastern portion.

Monroe, Summers, and Mercer counties.—In 1929 gas was discovered in the Indian Mills sand at a depth of 3,105 feet in a well

drilled near Bozoo, Red Sulphur district. Open flow from this sand was estimated at 239,000 cubic feet. The total depth of the well was 3,522 feet. A second well was drilled, somewhat more than a mile from the first, in the edge of Summers County. It encountered the Squaw sand at 2,820 feet, and at a depth of 2,916 feet struck a flow of gas estimated at 2,500,000 cubic feet daily with a pressure of 635 pounds. These wells were located on a dome along the Abbs Valley anticline, which was described in 1926 by the West Virginia Geological Survey[19] as a favorable locality for gas prospecting. The wells are more than 40 miles from the nearest gas pool in Wyoming County, more than 50 miles from well known gas areas in Raleigh, Fayette, and adjacent counties, and are some distance east of the 80 carbon-ratio line. D. B. Reger states that the average carbon ratio of 4 samples of Merrimac coal (Pocono age) in the county is 79.

The sands in the Pocono in northwestern Monroe County might offer some chances for gas as well as those in the Oriskany and White Medina ("Clinton").

Wyoming County.—In 1929 several wells encountered small amounts of gas near McGraw, in the Slab Fork district, along the Mullens anticline. The gas is said to have been from the Princeton sandstone, of Mauch Chunk age, and the wells had measured capacities of from 150,000 to 600,000 cubic feet each. V. C. Smith[20] made the following statement.

> Several wells completed in Wyoming County, W. Va., developed gas from the Maxon and Big Lime. It is very notable that these developments prove the existence of commercial gas reserves in areas where the carbon ratio exceeds 65, and definitely indicates that new fields will be opened to the east, closer to the major markets.

Carbon ratios in this county are from about 70 to more than 80.

McDowell County.—In 1933 a well in the Big Creek district encountered 213,000 cubic feet of gas in the Berea sand at about 3,950 feet. It was drilled to the top of the Oriskany at 6,639 feet, where the tools stuck and could not be recovered. D. B. Reger[21] states that

> in Browns Creek district, in this county, active drilling is in progress within the city limits of Welch, where gas wells of small capacity and only nominal rock pressure are being found in the outcropping or thinly buried sands of the Pottsville series (Penn.). Details of this discovery are not complete, but 20

[19] D. B. Reger, *West Virginia Geol. Survey County Report on Mercer, Monroe, and Summers Counties* (1926), pp. 142, 657.

[20] V. C. Smith, in *Petroleum Development and Technology 1933* (Amer. Inst. Min. Met. Eng.), p. 283.

[21] D. B. Reger, *Petroleum Production, 1934* (Amer. Inst. Min. Met. Eng., 1935), p. 51.

wells or more have been drilled. The known presence of a vast amount of gas, which is being released daily by coal mining in this region, indicates a possibility that the gas found at Welch may be percolating through broken strata toward the outcrop.

Carbon ratios here are from about 70 to 80.

VIRGINIA

In southwestern Virginia, where the carbon ratios range from about 60 in Lee County to about 70 in Scott County, and more than 75 in eastern Buchanan, gas may possibly be developed at localities of favorable underground structure.

Scott County.—A well in the southeast corner of Scott County, about a mile southwest of the junction of Catherine Branch with Cove Creek (covered by the Bristol topographic map) was reported in 1931 to have encountered about 1 million cubic feet of gas with 1,350 pounds rock pressure. The productive horizon was said to be near the bottom of the well, which was down 3,800 feet. Another well was drilled in 1932 on the Smith farm east of Gate City, not far from well No. 1 in Scott County. The well on the Smith farm was reported to have reached a depth of 5,610 feet before it was abandoned and to have struck a small flow of gas at 5,010 feet.

A short report by Charles Butts[22] describes the geology and structure of this area.

Rocks from which oil or gas might be derived are known to underlie the area and there are also sandstones of sufficient porosity to serve as adequate reservoirs. The carbon ratios in this region are probably about 70, and the chances for finding gas are much better than for oil in commercial quantities.

Lee County.—In 1923 a little oil was reported in a well drilled in Rose Hill in Lee County, and a press notice briefly describing the geology and structure of the area was issued by the United States Geological Survey.[23] Charles Butts, the geologist who examined the well, stated that the oil oozed from the Clinton formation, which is surrounded and apparently overlain by the Knox dolomite as the result of an overthrust fault. The overthrusting of the rocks relieved the stresses of lateral pressure, and coals north of Rose Hill in Lee County are found to have a carbon ratio of only about 60.

Buchanan County.—Gas seepages were reported in shallow water wells drilled some years ago in the central part of Buchanan County,

[22] Charles Butts, "Oil and Gas Possibilities at Early Grove, Scott County, Va.," *Virginia Geol. Survey Bull. 27*, prepared in coöperation with *U. S. Geol. Survey* (1927).

[23] Charles Butts, "Oil in Lee County, Virginia," *U. S. Dept. Interior Press Mem.* (July 3, 1923).

and in 1932 a well drilled on the "Smith Farm" was said to have encountered a showing of gas at a depth of 5,010 feet. This well was abandoned at a depth of 5,610 feet.

Wise County.—A well was started by Benedum and Trees in 1932 on the Kaufman lease on Guest River, and in June, 1933, it was reported to be at a depth of 3,350 feet. Many years ago a well was drilled in search for oil or gas near Ramsey on Clear Creek, and reached a depth of 2,153 feet. A slight flow of gas was encountered at 626 feet. In 1920 when this well was visited by Eby, the flow of gas was "insignificantly small." In a report on this county, Eby[24] mentions and shows on his map structures that offer some chance for the discovery of gas pools.

In central, southern, and western Wise County the carbon ratio is about 62.5, while in the eastern and northern parts of the county it is 65 or more.

There is reproduced a map by Eby (Fig. 3) showing carbon rations in southwest Virginia.

KENTUCKY

Bell and Harlan counties.—A well was drilled near Beverly Post Office on Red Bird Creek, in Bell County, in 1930, by the Asher Coal Mining Company. The well was reported in oil journals to have an elevation of 1,300 feet and went to a depth of something over 2,600 feet ("in the Big lime") encountering 1,048,000 cubic feet of gas. A second well was drilled just south of Beverly and was reported to have struck 300,000 cubic feet of gas at a depth of about 3,725 feet. In 1931 a well drilled near Four Mile Creek went to a depth of 2,748 feet and encountered showings of oil and gas at several horizons.

Carbon ratios in this county are around 60, and this is also true of Letcher County.

Pike County.—That there have, for years, been gas developments in western Pike County is not surprising, but the eastern part of the county probably also has gas prospects, though the carbon ratios here are 65 or more. In this connection it is of interest that some years ago (about 1920) a well near Elkhorn City, completed to a depth of 1,223 feet, was reported to have a production of about 10 gallons per day of "green crude" oil.

A well drilled by the United Fuel Company near Jamboree in Pike County encountered an estimated 42,000 cubic feet of gas. The bottom of the well is in the Corniferous at a depth of 4,889 feet.

[24] J. B. Eby, "The Geology and Mineral Resources of Wise County and the Coal-Bearing Portion of Scott County," *Virginia Geol. Survey Bull. 24* (1923).

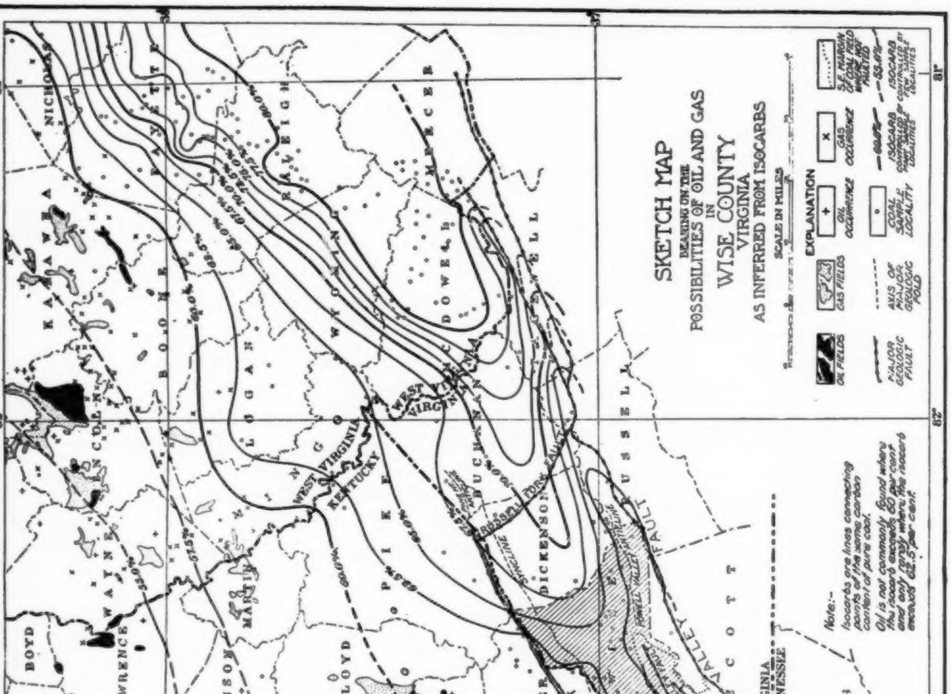

FIG. 3.—Sketch map bearing on possibilities of oil and gas in Wise County, Virginia, as inferred from isocarbs. Taken from *Virginia Geol. Survey Bull. 24* (1923).

Another well, 2 or 3 miles north of Elkhorn City, drilled to a depth of 4,900 feet by the Howe Oil and Gas Company, had an initial production of 116,000 cubic feet of gas. Gas has been found in the Pottsville and in the "Big lime" in Pike County, but several other horizons offer promise for the production of gas.

During the field season of 1934, the United States Geological Survey conducted, as a Public Works project, investigations of the coal resources of Pike County, and has accumulated incidental material relating to natural gas conditions.

TENNESSEE

With regard to Tennessee, the following statement has been made by L. C. Glenn.[25]

> Gas occurs near Sunbright and Glenmary at the same horizons as the oil there. Some wells have two to three million feet open flow with closed pressure of 150 to 200 lbs. Plans are being made to pipe the gas to several near-by towns and to Knoxville. Additional drilling is necessary before the extent of the gas field can be determined. . . . At a number of places, especially on the northern and eastern Highland Rim, from the Kentucky line around east and south to Alabama, gas has been obtained at depths that range from 200 or 300 to 1,200 ft. from weathered porous zones that mark unconformities in Ordovician limestone. The open-flow volume is often several million feet. Closed-in pressures are usually low. Such wells are found near Red Boiling Springs, Cookville, Sparta, McMinnville, and Smithland.

Additional supplies of natural gas for industrial use will, it is believed, be found in various counties in Tennessee. When the Tinsley Bottom field in Clay County was at the peak of its oil production in the period 1925–1928, large quantities of gas were permitted to blow off and no attempt made for its conservation.

In 1931 gas from 14 wells in Lincoln County was used in Fayetteville, a few wells in Warren County served McMinnville, 2 wells near Sparta in White County were expected to serve that town, and several near Cookville in Putnam County were supplying gas locally. In 1930 an interesting occurrence of gas was reported in Overton County near Livingston, the production being from the "St. Peter" at a depth of about 1,760 feet. Gas was reported found in this same formation at Carthage in Smith County. The "St. Peter" sand in Tennessee is believed to have a thickness ranging from 50 to 100 feet and overlies the Knox dolomite. It averages about 1,100–1,200 feet below the base of the Chattanooga shale.

[25] L. C. Glenn, "Oil and Gas Production in Tennessee in 1933," *Petroleum Development and Technology, 1934* (Amer. Inst. Min. Met. Eng.).

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ECONOMIC SPACING OF OIL WELLS[1]

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ABSTRACT

The use of wider spacing and the consequent drilling of fewer wells appear to be a promising procedure for necessary and important reductions in the cost of producing oil. It is believed that petroleum geologists and petroleum engineers have a very important rôle to play in studying the various characteristics of the producing reservoir as a basis for a suitable and efficient development and production program.

Introduction

Petroleum geology has become more and more complex, but it remains fundamentally an economic science. Its primary purpose is to render profitable service to the petroleum-producing industry. One of the most important problems of this industry is the economic spacing of wells. Many of the factors involved in this problem are of a geological nature. It seems certain that petroleum geologists, as well as petroleum engineers, have an important field, at present only partly explored, in applying their science to this problem.

Definition of Ecomonic Spacing of Wells

Probable *net* return is admittedly a fundamental question in planning the drilling of additional locations around a discovery well. For the purposes of this paper it is assumed that unless an added well seems likely to yield sufficient *additional net* income to permit a fair margin of profit, its drilling must be considered uneconomic. It is obvious that the probable *net* return from the added well may vary widely according to several factors, such as drilling and production costs, total yield, and probable average price for oil. Also, the "fair margin of profit" will vary somewhat according to the probability of profitable yield. Interest on investment and present worth of future

[1] Read in preliminary form before the Association at Dallas, March 23, 1934. Manuscript received, March 5, 1935.

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net return require proper consideration. In spite of relatively high prices for oil, many good oil pools in the past have been developed and produced at a loss to the oil producers. Present low or moderate prices for oil compel careful scrutiny of each item of expense and particularly such large appropriations and risks as those involved in the drilling of additional wells.

Royalty owners can not logically expect the oil producer to strive for additional oil at costs which prohibit a fair margin of profit. Fortunately, the evidence now available supports the view that percentage recovery of oil from the reservoir commonly depends less on the close spacing of wells than on such other factors as the proper utilization, conservation, and maintenance of reservoir energies.

Suman[3] has recently expressed the opinion that close spacing of wells often leads to inefficient or improper use of available energy; therefore, it is very likely to be detrimental rather than beneficial to ultimate yield. He cites the restoration of a densely drilled pool from apparent exhaustion to flowing life by repressuring with gas as evidence that production practice rather than close spacing (300-foot interval in this pool) is the essential factor. Concrete evidence of this nature, as well as many theoretical considerations, supports the view that the spacing of wells is only one of many important factors in oil recovery.

Curtailment of Development Expenditures Necessary

In common with producers of other commodities, oil operators are doubtless faced with the prospect of many years of low-to-moderate prices for their products, judging by records of other post-war periods. Current huge potentials, marked advances in methods of discovery, world-wide exploration, ever-increasing drilling range, competition with oil from extensive efficiently managed foreign concessions, greatly improved drilling, producing and refinery methods, government regulation, high sales taxes on gasoline, and the trend toward increased efficiency in the use of fuel and lubricants in motors, all portend moderate prices for petroleum and its products for many years. Oil producers must, therefore, diligently seek reduction in producing costs to meet this tremendous reduction of income, which is likely to average about $500,000,000 less per year for the decade 1931–1940 than during the preceding 10 years, in spite of greater total production.

[3] John R. Suman, "The Well Spacing Problem: Low Well Density Increases Ultimate Recovery," *Oil Weekly* (May 28, 1934), pp. 43–46; also *Amer. Petrol. Inst. Prod. Bull. 214* (November, 1934).

Where Practical, Wider Spacing Effects Large Savings

Commonly, no other item adds so much to the cost of producing oil as the outlay for drilling and equipping wells. This expense can be reduced by almost 75 per cent if the distances between wells are doubled. Further savings may be accomplished because of prolonged flowing period and reduced lifting costs. Doubtless in many regions where wells have been spaced with 150-foot radii, a 330-foot radius can be adopted without sacrifice of acreage yields, provided proper well equipment and production control methods are used. Similarly, many other areas having more continuous and permeable reservoirs now accustomed to 330-foot radii could change this to 466.5 feet with an approximate saving of 50 per cent with little or no loss in ultimate yield. Most favorable conditions may permit even much wider spacing than this.

It must be emphasized from the outset, however, that such factors as the capacity, permeability, continuity, and structure of the oil-berring reservoir and the presence or absence of a water drive largely prescribe the limitations in the proper spacing of wells in any pool. Obviously, the initial spacing plans should be made as flexible as possible, subject to necessary adjustment as actual conditions become known.

Engineering Advances Revolutionizing Oil-Producing Industry

No doubt wider spacing will become both more practical and generally adopted under proration restrictions and more general operation of oil pools as units. In all probability, public interest and the competition faced by the producers of this country will soon necessitate changing former practices based on the law of capture to practices based on efficiency. There is much reason to believe that by the use of bottom-hole pressure gauges, the withdrawals from most reservoirs may be so regulated that reservoir pressure is kept equalized throughout the pool, in which cases oil and gas need no longer be regarded as "fugacious." Serious efforts toward high ultimate yields per acre at low costs per barrel are recent innovations for this industry. These objectives have long been considered desirable by most oil operators, but commonly impossible of attainment under prevailing court decisions. Proration by agreement or by governmental regulation is, in effect, revolutionizing the oil-producing industry by placing correlative rights and high percentage recoveries above individual advantage and wasteful production practices. Doubtless vertical drilling, improved production technique, and the establishment of equit-

able principles for allocation of production within a prorated pool, such as those being formulated by the Allocation of Production Committee of the American Petroleum Institute,[4] will greatly expand the usefulness of well-spacing studies.

Field Evidence Regarding Size of Drainage Area

That a well can drain a relatively large area is evidenced by many records of actual performance. Certain wells subjected to less interference than usual have yielded as much oil as might be expected from several wells with conventional spacing. In other wells long flowing life and high individual yield have apparently resulted from more efficient production methods. Cases illustrating these types are cited herewith.

A disappointing well flowing only 125 barrels of oil per day was completed at a depth of 3,900 feet in Stephens County, Texas, in June, 1924. This production seemed too small to encourage near-by drilling. The decline in daily production during the first 10-year period has been but 25 per cent, with a total yield of more than 325,000 barrels from a productive horizon which commonly averages less than 3,000 barrels per acre. Another well, located in southeast Young County, Texas, completed at a depth of 2,500 feet, from a Strawn sand, was still able in its eleventh year to flow 90 barrels per day against 125 pounds tubing pressure, in spite of its past yield of 1,400,000 barrels. The Strawn sands of this district rarely yield more than 10,000 barrels per acre This well with initial yield of about 40 barrels per hour was "pinched in" two weeks after completion to prevent wastage of gas,—an important factor usually neglected in bygone years during which most current spacing practices were adopted. Also, this well suffered no interference from near-by wells for more than 10 years.

Evidently, spacing formulas, as suggested by Haseman and Phelps,[5] if attempted at all, must be developed with extreme care to fit actual conditions, and are certain to exhibit an extremely wide range of values and results as between pools of different types Haseman listed eighteen factors other than well spacing as affecting ulti-

[4] *Amer. Petrol. Inst. Bulletin*, 1934 Annual Volume, *Drilling and Production Practice*, pp. 1–34.

[5] W. P. Haseman, "A Theory of Well Spacing," *Trans. Amer. Inst. Min. Met. Eng.* (1930), Petrol. Div., pp. 146–56.

———, "A Formula Method for Well Spacing and Rate of Production," *National Petrol. News* (May 8, 1929), 7 pp.

R. W. Phelps, "Analytical Principles of the Spacing of Oil and Gas Wells," *Petroleum Development and Technology, 1928–29* (Amer. Inst. Min. Met. Eng.), pp. 90–103.

mate recovery. One of these other factors was the "mode of operating wells," which itself involves many important factors not mentioned in this list.

Prolonged large production by a cratered well in the Conroe field, without pressure decline in near-by wells, is cited by Deussen[6] as evidence that this one well in time could have produced most, or perhaps all, of the recoverable oil in that part of the reservoir subject to drainage by this well.

Wood,[7] who served several years as chairman of the Well Spacing Committee of the American Petroleum Institute, has stated his belief that there is no known limit to the distance that oil may migrate through a continuous reservoir to a well. The ease with which oil may migrate, if energy is available, is demonstrated by reservoir rocks with pores too small to be permeable to water which are found to be readily permeable to crude oil of 45° Bé. gravity, according to Nutting.[8]

Late drilling of five-spot wells for repressuring an oil pool in Kansas disclosed that the water table had advanced uniformly into reservoir areas originally above the water level. The original spacing of wells in this normal sand reservoir was about one well per 7 acres. Technical advisers now believe that one well per 14 or even 28 acres, with restricted rather than open-flow production, would have been better practice for this pool.

Doubtless, numerous examples may be cited where added wells closely spaced have secured sufficient additional oil to return some profit, an outstanding case being that of the large Healdton field in southern Oklahoma, where the original spacing was comparatively close, yet many 5-spot wells, drilled 15 years or more after the original development work ceased, have had initial yields and stamina sufficient to be considered profitable.[9] The explanation in this case perhaps lies in the presence of a thick series of very lenticular sands, and a comparatively heavy oil under relatively low pressure and without sufficient free gas or water drive to make wide drainage possible.

ANALYTICAL AND EXPERIMENTAL EVIDENCE

Investigations regarding the character and behavior of oil, gas, and water in natural reservoirs and producing wells have brought

[6] Alexander Deussen, oral discussion, March, 1934.

[7] Fred E. Wood, discussion, November, 1933.

[8] P. G. Nutting, "Some Physical and Chemical Properties of Reservoir Rocks Bearing on the Accumulation and Discharge of Oil," *Problems of Petroleum Geology* (Amer. Assoc. Petrol. Geol., 1934), p. 829.

[9] C. W. Tomlinson, correspondence, March ,1934.

forth interesting deductions which in practice need to be correlated with related factors of a geological nature. Numerous reports of these studies have been published by the United States Bureau of Mines, United States Geological Survey, American Petroleum Institute, American Institute of Mining and Metallurgical Engineers, and various periodicals, including the Association *Bulletin*.

Herold's[10] extensive analytical studies "on fluid delivery from oil and gas wells" brought him to the conclusion that, based on productive performance, reservoirs may be grouped into three types as follows: "hydraulic control," where pressure and rate of production do not diminish; "volumetric control," where pressure and rate of production decline, with pressure lowering according to production rate; and "capillary control," where pressure and rate of production decline *as if* alternate globules of liquid and bubbles of gas in capillaries were impeding the flow to the well. Water pressure is the main expulsive agent in the first type, water and gas in the second (most common type), and gas in the third. Obviously, these three "controls" favor high percentage recoveries and wide spacing of wells in the order named. However, it is evident that the rate of production may determine whether a well or pool produces its oil under hydraulic or volumetric control, and that repressuring or flooding may convert a more or less depleted pool from "capillary" to "volumetric control." Evidently his conclusions regarding the small limits of drainage under the "capillary control" system were based largely on the assumed effect of bubble resistance noted in such combinations as air and water in capillary tubes. These pools may act as if so influenced, but, as noted by the discoverer of this phenomenon, and recently called to our attention by Wright,[11] this "Jamin" effect does not apply to oil and gas mixtures; therefore, this obstacle to wide spacing is less insuperable than assumed by Herold in oil pools of this type. The comparatively rapid decline under "capillary control" more probably represents a rapid exhaustion of reservoir energy, a condition preventable by efficient operating methods and return of fluids to the reservoir.

[10] Stanley C. Herold, *Analytical Principles of the Production of Oil, Gas, and Water from Wells* (Stanford University Press, 1928), 659 pp.

———, "Jamin Action—What It Is and How It Affects Production of Oil and Gas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 12, No. 6 (June, 1928), pp. 659–70.

———, "The Trend in Petroleum Technology," *Oil Weekly* (February 4, 1935), p. 27.

[11] Randall Wright, "Jamin Effect in Oil Production," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 17, No. 12 (December, 1933), pp. 1521–26.

See also R. D. Wyckoff, H. G. Botset, and M. Muskat, "The Mechanics of Porous Flow Applied to Water-flooding Problems," *Trans. Amer. Inst. Min. Met. Eng.* (1933), Petrol. Div., p. 239.

Results of recent investigations of special interest include the following. Lindsly's[12] studies of samples of oil captured at the bottom of wells in the East Texas field show that this oil has 60° Bé. gravity (probably having the fluidity of kerosene) in its natural reservoir state; that 80 barrels of oil in the stock tank represents 100 barrels of oil with its dissolved gas in the reservoir; that, whereas lifting one cubic foot of oil 3,600 feet represents 169,500 foot-pounds of work done, the energy available from the expansion of the gas dissolved in this amount of East Texas oil varies from 328,800 to 433,300 foot-pounds. Yet this particular oil is known to have much less than the ordinary amount of dissolved gas for similar depth and gravity, no gas being liberated until pressure is reduced to about 50 per cent of the original reservoir pressure in this field.

In most oil fields there is originally available a great supply of energy to be derived from sources other than this dissolved gas, such as the expansion of associated free gas and the encroachment of water, the latter being a replenishing source of energy in varying degree. In high-pressure fields associated with extensive water-filled reservoirs, fluid expansion alone must be an important factor, as recently emphasized by Schilthuis and Hurst.[13] Some expulsive force may come from compaction of the reservoir by the weight of the overburden if the reservoir is unconsolidated.[14] Doubtless more energy is commonly available in reservoirs under volumetric or hydraulic control than is needed to bring the oil laterally to the well from considerable distances and lift it to the surface, if efficient methods of production are practiced. Large percentage recoveries seem reasonably to be expected from pools under "capillary" control with wells spaced as widely as one well to 20 or possibly more acres, provided geologic conditions are favorable and natural energies are properly utilized. The addition, if need be, of energy to the reservoir by mechanical means can be accomplished at less cost than now commonly entailed in efforts to secure high recovery by excessive drilling.

The results of experiments by Uren and Bradshaw[15] appear very

[12] Ben E. Lindsly, "A Study of 'Bottom Hole' Samples of East Texas Crude Oil," *U. S. Bur. Mines R. I. 3212* (May, 1933), 27 pp.

[13] R. J. Schilthuis and William Hurst, "Study of Variations in Reservoir Pressure in the East Texas Field," *Trans. Amer. Inst. Min. Met. Eng.* (1933), Petrol. Div., also *Oil and Gas Jour.* (October 18, 1934).

[14] In the East Texas oil field, compaction of the reservoir may prove very important, according to J. S. Hudnall in a paper delivered at the annual meeting of the Association, March 23, 1934. However, Minor and Hanna believe "the loose sand cores of the field are not due to the sand in place being loose, but rather to the method of coring." H. E. Minor and Marcus A. Hanna, "East Texas Oil Field," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 17, No. 7 (July, 1933), p. 772.

[15] L. C. Uren and L. J. Bradshaw, "Experimental Study of Pressure Conditions

significant. This work indicates that increasing the distance of lateral migration of oil in a reservoir would increase only slightly the amount of energy consumed, for most of the energy is used in the immediate vicinity of the well where fluids must move with increasing velocity. Work done in moving active oil to the well is mainly a matter of overcoming frictional resistance which must be negligible in the outer large concentric circles where the movement of oil toward the well is exceedingly slow. Possible interference by gas bubbles near the well can be largely counteracted by maintenance of reservoir pressure and back pressure in the wells, the effects of pressure doubtless being both to lessen the escape of gas from solution and to compress the gas bubbles, thereby facilitating passage through the small interstices which connect the larger pore spaces.

Contributions of particular interest have been made by Lacey,[16] such as his paper entitled "Practical Benefits of Pressure Maintenance in Petroleum Production." The very decided changes in amounts of dissolved gas, surface tension, viscosity, volume, and gravity of the oil caused by changing pressures are well illustrated in this paper. He supports earlier investigators in demonstrating that "Dissolved gas lowers viscosity and surface tension of crude oil to a remarkable degree, thus promoting drainage to wells."

H. C. Miller,[17] of the United States Bureau of Mines, has prepared a very comprehensive treatise entitled *Function of Natural Gas in the Production of Oil*. This book, distributed by the American Petroleum Institute, emphasizes how exceedingly important a factor is the accompanying gas which has been treated as a troublesome byproduct in oil production during the years when our common well-spacing practices were being developed.

Notable progress in the study of porosity and permeability of reservoir rocks has been made recently.[18] It is to be expected that oil

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Within the Oil Reservoir Rock in the Vicinity of a High-Pressure Producing Well," *Trans. Amer. Inst. Min. Met. Eng., 1932*, Petrol. Div., pp. 438–66.

[16] William N. Lacey, "Practical Benefits of Pressure Maintenance in Petroleum Production," *Proc. 13th Ann. Meeting Amer. Petrol. Inst.*, Sec. IV, *Prod. Bull. 210* (1932), pp. 16–28.

[17] H. C. Miller, *Function of Natural Gas in the Production of Oil* (Amer. Petrol. Inst., 1929), 267 pp.

[18] C. M. Nevin, "Permeability, Its Measurement and Value," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 4 (April, 1932), pp. 373–84.

G. H. Fancher, J. A. Lewis, and K. B. Barnes, "Some Physical Characteristics of Oil Sands," *Pennsylvania State College Min. Ind. Exp. Sta. Bull. 12* (1933), pp. 65–171.

Moore, R. J. Schilthuis, and William Hurst, "The Determination of Permeability from Field Data," *Amer. Petrol. Inst., Prod. Bull. 211* (May, 1933), pp. 4–13.

R. D. Wyckoff, H. G. Botset, M. Muskat, and D. W. Reed, "Measurement of

operators will recognize more and more the value and necessity of greater detailed study of the productive reservoirs which they have made large capital outlays to penetrate.

Certain discussions[19] on well spacing based upon results obtained from pools with limited energy and/or produced under highly wasteful and competitive methods of production, are thought to have little if any bearing upon the results which can be obtained under the orderly, efficient production practices which it is assumed the oil industry and governmental conservation agencies will choose to adopt for future development work. Very practical analyses and comprehensive reviews of literature on this subject have been presented recently by Lewis[20] and Rhys Pryce.[21] Many of the fundamentals involved were helpfully discussed at an earlier date by Brewster and Uren.[22]

Upon first thought, the large pressures and close spacing required in water-flooding operations, as in the Bradford field, seem to emphasize the difficulty of securing high recoveries without close spacing. However, the problem of forcing a thick wall of oil through these depleted sands of low permeability, ranging from 1/500 to 1/50 of the permeability of the better sands of the East Texas field,[23] is vastly

Permeability of Porous Media," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 18, No. 2 (February, 1934), pp. 161–90.

Charles R. Fettke, "Physical Characteristics of Bradford Sand, Bradford Field, Pennsylvania, and Relation to Production of Oil," *ibid.*, pp. 191–211.

Report of Topical Committee on Development and Production Research, "Proposed A.P.I. Code for Permeability Standardization," *Amer. Petrol. Inst. Prod. Bull. 214* (November, 1934), p. 72 and report to be published.

[19] W. W. Cutler, Jr., "Estimation of Underground Oil Reserves by Oil Well Production Curves," *U. S. Bur. Mines Bull. 228*, pp. 85–90.

W. P. Haseman, "Theory of Well Spacing," *Trans. Petrol. Div. Amer. Inst. Min. Met. Eng.* (1930), 10 pp.

———, "A Formula Method for Well Spacing and Rate of Production," *National Petroleum News* (May 8, 1929), 7 pp.

R. W. Phelps, "The Relation of Oil Recovery to Well Spacing," *Amer. Petrol. Inst. Prod. Bull. 210* (1932), pp. 93–100.

Dwight C. Roberts and Stender Sweeney, "Spacing of Wells in the Long Beach Field," *Petroleum Development and Technology, 1930* (Amer. Inst. Min. Met. Eng.), pp. 156–59.

A. Young, "Correct Spacing for Wells," *The Oil Weekly* (May 1, 1931), pp. 26–29.

[20] James O. Lewis, "Comparison of Spacing Problems in Gas Drive with Those in Water Drive Pools," *Trans. Petrol. Div. Amer. Inst. Min. Met. Eng.* (October meeting, 1934). *The Oil and Gas Jour.* (October 11, 1934), pp. 38–39.

[21] M. A. AP Rhys Pryce, "Some Considerations Affecting the Spacing of Oil Wells," *Jour. Inst. Petrol. Tech.*, Vol. 20 (October, 1934), pp. 951–72.

[22] F. M. Brewster, "A Discussion on Some of the Factors Affecting Well Spacing," *Petroleum Development Technology, 1925* (Amer. Inst. Min. Met. Eng.), pp. 37–46.

L. C. Uren, "The Elements of the Oil-Well-Spacing Problem," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 9 (March-April, 1925), pp. 193–216.

[23] G. H. Fancher, J. A. Lewis, and K. B. Barnes, *op. cit.*, pp. 142–49.

different from the natural drainage to a well of small accretions of oil from a slowly expanding drainage area in which the oil has internal energy measured initially in tens and hundreds of thousands of foot-pounds per cubic foot Also, the time used in performing the work of recovery is commonly a matter of months for artificial water drives in contrast to years when natural reservoir energies are utilized.

Had wide spacing been practiced in the past wherever reservoir conditions permitted, investment and expense would be in better ratio to income, output could be more easily adjusted to consumers' needs, and there would be less hue and cry for larger allowables per well. Such widely-spaced fields as Yates and Conroe present great contrast to closely-spaced fields like Hendricks and East Texas in their effects on the industry and cost per barrel of oil produced. A more uniform rate of drilling activity, occasioned by less precipitate development of known pools, and a more regular rate of search for new pools would seem to be advantageous to all those involved in the oil-producing industry.

Physical Problems of Well Spacing and Oil Recovery

In a consideration of the physical problems of well spacing and oil recovery, it is evident that these resolve mainly into detailed studies of the reservoir, its fluids, and the efficient use of the available energy in delivering the oil to the well and to the surface.

It is apparent, first of all, that several variable factors are involved; therefore, that each pool demands individual analysis. Also, different parts of a sizeable pool may have individuality and require different spacing treatment. In locating the initial test, the geologist and engineer are called on to predict the probable conditions, using information gained from previous experience with productive reservoirs of the same age and type as expected in the test well, and other factors such as the gravity of the oil, probable structural conditions, and the amount and sources of reservoir energy. These predictions are important, for the location of the discovery well with respect to lease ownership lines, and the size of lease subdivisions arranged at the time of the drilling of the initial test, commonly determine the spacing pattern for the entire pool.

RESERVOIR FACTORS

RESERVOIR CAPACITY AND ESTIMATED ULTIMATE YIELD

The estimation of the amount of recoverable oil present in the reservoir is an important consideration in determining the percentage recoveries obtained and in prescribing limits for development ex-

penditures, which must be kept safely below the expected net operating income. This estimation of recoverable oil must depend mainly on a careful determination of the total volume of effective pore space occupied, which is to be multiplied by a suitable recovery factor. The recovery factor must be chiefly a matter of judgment based on several factors, such as the probable amount of available energy, permeability of reservoir, character of oil, amount of dissolved gas, production methods, et cetera.[24] Doubtless, bottom-hole oil samples and bottom-hole producing pressure tests[25] will furnish much important basic data for this purpose in the future.

The approximate percentage of effective pore space may be determined from cores of the productive reservoir, according to the usual methods.[26] Comparison of results obtained from various wells as the pool is developed will be needed to check the lateral continuity of conditions found in early wells and to revise, if necessary, the earlier estimates and spacing plans. The degree of saturation should receive investigation, particularly in development work late in the life of a pool. In consolidated reservoirs, the space afforded by joints, fractures, and bedding planes must be given due consideration, as emphasized by the production of oil and gas from certain shale reservoirs and dense limestones.

The effectiveness of recovery efforts can not be calculated unless the approximate original oil content of the reservoir is known. It is entirely probable that in past years the actual percentage recoveries have been considerably higher than heretofore thought, because of the tendency to overestimate the thickness of the oil sand and its average effective porosity (in some cases amounting to 10 per cent less volume than total porosity)[27] and to neglect the large shrinkage which occurs because of the escape of dissolved gas and temperature change. Lindsly[28] found that the reservoir space occupied by oil and its dissolved gas in the East Texas and Kettleman Hills fields is 25 and 50 per cent greater, respectively, than the volume of the oil alone as measured in the stock tanks.

[24] O. L. Brace, "Factors Governing Estimation of Recoverable Oil Reserves in Sand Fields," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 18, No. 3 (March, 1934), pp. 343–57.

[25] C. V. Millikan, "Geological Application of Bottom-Hole Pressures," *ibid.*, Vol. 16, No. 9 (September, 1932), pp. 898–904.

[26] G. H. Fancher, J. A. Lewis, and K. B. Barnes, *op. cit.*
H. R. Brankstone, W. B. Gealy, and W. O. Smith, "Improved Technique for Determination of Densities and Porosities," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 9 (September, 1932), pp. 915–23.

[27] G. H. Fancher, J. A. Lewis, and K. B. Barnes, *op. cit.*, p. 119.

[28] Ben E. Lindsly, "Effect of Gas Withdrawal Upon Reservoir Fluids," *Trans. Amer. Inst. Min. Met. Eng.* (1934), Petrol. Div., pp. 94–97.

That large quantities of oil are likely to remain in the reservoir under inefficient operating practices is well demonstrated by flooding recoveries from the depleted Bradford field. The oil-mining operations in the Pechelbrönn field, Alsace, have also been cited frequently as especially convincing proof of small recovery obtainable by ordinary production methods. It should be noted, however, as reported by Rice and Davis,[29] that in this field the oil has a gravity of 14.5°, 18°, and 29° Bé., there is no water and very little gas associated with the oil, and the sand bodies are thin, have a high clay content, and are interrupted by many faults, veinlets, and seamlets. Under these very adverse conditions, a recovery of 16.7 per cent by flowing and pumping seems reasonable. High-percentage recovery from such a field would no doubt require relatively close spacing and much pressure-maintenance work.

PRODUCING PERMEABILITY; STANDARD PERMEABILITY

The permeability of the producing reservoir to its fluid contents is of major importance in outlining a well-spacing program. The facility with which the contained oil (with its dissolved gas) flows through the reservoir rock, herein called "producing permeability," and the lateral continuity and vertical consistency of this property are supremely important in estimating how large an area can be effectively drained by a well under conditions expected to prevail in a given pool. Comparison of initial productive capacity of wells completed under like conditions of reservoir pressure, et cetera, will approximately reveal certain important traits of the reservoir, large flow indicating high permeability and initial yields in a pool indicating the lateral uniformity, or otherwise, of this property. A careful check of increasing yield of oil and gas when the wells are being drilled into the reservoir may afford an index of the vertical consistency of permeability. The distance between wells which affect each other during individual open-flow tests and the rapidity with which pressures build up when a well is closed in are other indicators of the "producing permeability" observable in field operations.

That reservoirs vary greatly as to permeability has been repeatedly emphasized, but the critical question for present purposes of how permeable the reservoir is to *its* fluid contents has received less comment. It is well known that oils differ greatly in viscosity and surface tension according to their chemical nature, and that a given oil will show a wide variation in these properties according to the physical

[29] George S. Rice and John A. Davis, "Mining Petroleum in France and Germany," *Petroleum Development Technology, 1925* (Amer. Inst. Min. Met. Eng.), pp. 278–314.

conditions under which it occurs or is held. Beecher and Parkhurst[30] were among the first to stress how greatly the viscosity and surface tension of an oil are affected by pressure and temperature. The surprisingly large differences in fluidity of an oil, due to temperature changes alone, must not be overlooked. Uren and Bradshaw[31] report that an asphaltic-base crude of 21.3° A.P.I. gravity had a viscosity of 0.92 poises at 65° F. and 0.073 poises at 210° F. Under laboratory tests with 400 pounds initial pressure, the resulting flow at the higher temperature was about 16 times greater than at the lower temperature. Reservoir temperatures, such as 146° F. in the East Texas field and 185° F. in the Big Lake field, must have a very important effect on the mobility of the oil. According to Heald,[32] the temperature of the reservoir remains practically constant during the life of a field.

As has been stated,[33] "it is highly desirable to know the average permeability of the entire sand section around a well to fluids as they exist in the reservoir." This information is revealed in large degree by determining the "productivity factor," defined as "the number of barrels per day which a well produces for each pound difference in pressure between the well and the surrounding reservoir," or "the rate of production, divided by the difference between the shut-in and the flowing pressures." The "specific productivity," defined[34] as the "productivity factor divided by the number of feet of sand exposed to the well," gives results in the field suitable for making comparisons and somewhat comparable to results obtainable by capturing a bottom-hole sample of the fluid and passing this through an average sample of the reservoir rock under the same temperature and pressure conditions as exist in the reservoir. No doubt this permeability of a reservoir to its contents is of such importance in many cases that both field and laboratory studies should be made as a check against each other.[35] In some ways it seems impractical to put much dependence on results obtained from core samples which represent so small a part of the reservoir, particularly in the case of reservoirs in which much

[30] C. K. Beecher and I. P. Parkhurst, "Effect of Dissolved Gas Upon the Viscosity and Surface Tension of Crude Oil," *Petroleum Development and Technology in 1926* (Amer. Inst. Min. Met. Eng.), pp. 51–63.

[31] L. C. Uren and L. J. Bradshaw, *op. cit.*, pp. 449 and 452.

[32] K. C. Heald, "Determination of Geothermal Gradients in Oil Fields on Anticlinal Structure," *Amer. Petrol. Inst. Prod. Bull. 204* (January, 1930), p. 110.

[33] Moore, R. J. Schilthuis, and William Hurst, *op. cit.*, p. 4.

[34] *Ibid.*

[35] Note: Determination of permeability by both laboratory methods and well flowing tests is treated by Wyckoff, Botset, Muskat, and Reed in a particularly valuable paper, *op. cit.* The term "effective permeability" is used by these authors for permeability determined by flow tests with viscosity reduced to standard of one centipoise.

oil is stored in bedding planes or fractures. However, in many cases these core samples give much needed detailed information regarding the reservoir, including whether extra care must be given to production rates and methods. Rapid encroachment of water or rapid depletion of energy will undoubtedly give low percentage recoveries from reservoirs having wide vertical or lateral variations in permeability.[36]

The permeability of the reservoir and the mobility of its fluid contents in their natural state are so complementary in well-spacing problems that they deserve treatment as a single factor with definite unit value. This unit might be called the "darcy (restricted)," its use being reserved for determinations of "producing permeability," in contrast to the standard or specific permeability.[37] For the "darcy (restricted)," the same units of measurement are suggested as for the darcy, excepting that the actual viscosity of the fluid at its reservoir temperature and at designated pressures is used without converting to the standard viscosity of one centipoise. For well-spacing studies, pressures expected to be maintained during the later life of a pool are most critical, and for purposes of convenience and comparison the "producing permeability" might well be expressed as "darcys (restricted)" in multiples of 5 or 10 atmospheres (absolute). For example, a sand might be said to have a "producing permeability" of 4 darcys (restricted) at 20 atmospheres (absolute) if the trapped oil held at reservoir temperatures and 294 pounds pressure per square inch (absolute) passes through a representative core at the rate of 1 milliliter per second for each cubic centimeter of core with differential pressure of $\frac{1}{4}$ atmosphere per centimeter thickness. The use of bottom-hole oil samples from the reservoir in question and retained in the natural state by the bottom-hole sampling device, together with suitable equipment[38] to permit viscous flow with the core and fluids held at the same temperature as prevails in the reservoir, would permit determination of the "producing permeability" by laboratory meth-

[36] H. D. Wilde, Jr., and F. H. Lahee, "Simple Principles of Efficient Oil-Field Development," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 17, No. 8 (August, 1933), pp. 981–1002.

[37] The "darcy" as defined in the Proposed Amer. Petroleum Institute Code equals "the rate of flow in milliliters per second, of a fluid of one centipoise viscosity through a cross section of one square centimeter of porous medium, under a pressure gradient of one atmosphere (76.0 cm *Hg*), per centimeter and conditions of viscous flow (equals approximately 1.127 barrels per day, through a 1-foot cube of reservoir rock for each pound differential pressure).

[38] A hydraulic pump was used satisfactorily by Torrey for permeability tests up to 1,500 pounds pressure. Paul D. Torrey, "Modern Practice in Water-Flooding of Oil Sands in the Bradford and Allegany Fields," *Petroleum Development and Technology, 1930* (Amer. Inst. Min. Met. Eng.), p. 266.

ods. This procedure obviously involves certain difficulties. A practical compromise may be to determine both the permeability of the core (in the usual manner) and the viscosity of the oil at successive pressures by use of a "bottom-hole" sampler constructed and equipped to serve as a pressure viscosimeter, or used in connection with a separate pressure viscosimeter;[39] whereupon a permeability-viscosity quotient may be determined as an approximation of the "producing permeability" factor.

It is apparent that care must be exercised in the treatment of core samples which are to be used in determining the "producing permeability" as heretofore discussed. No doubt it will be necessary that the core be kept in contact with oil while the core is being taken, and thereafter that oxidation and drying should be prevented by keeping the representative core samples selected for analysis saturated with a suitable oil in an air-tight container as much as possible. The effect of surface tension of the oil is omitted in the standard permeability test, but would be automatically included by this treatment. Some other uncertainties involved in the usual permeability analyses would also be eliminated, such as the possible effects on the core from use of solvents, drying, oxidation, re-wetting, and adsorption of the test fluid. The *desideratum* is, of course, to duplicate as nearly as possible the actual reservoir conditions, particularly as these will exist during the more adverse period of recovery.

On investigation, it may prove unnecessary to attempt this refinement in determining the "producing permeability" for use in well-spacing studies, but, to the writer, it seems to afford a single direct measurement of an essential relation and a sounder basis for comparisons than other units or measurements generally recommended. The standard permeability determinations of the reservoir rock alone are insufficient and may be misleading because the effects of the actual viscosity, surface tension, and adhesion are omitted, and the core may be affected by the treatment given it. The "productivity factor" and "specific productivity" give very practical and useful data as to the flow of the oil through the reservoir under *existing* pressure differentials. The "specific productivity" measurement, if projected to future and more adverse conditions and converted to standard units, as suggested by Wyckoff, Botset, Muskat, and Reed,[40] would give an approximation to the "producing productivity." The use of "effective permeability" as defined[40] gives a basis for comparing reservoirs, but

[39] C. A. Beecher and I. P. Parkhurst, *op. cit.*, p. 57.

[40] R. D. Wyckoff, H. G. Botset, M. Muskat, and D. W. Reed, *op. cit.*, pp. 179–89.

is not a measure of the facility of movement of the oil in its host reservoir under natural conditions.

MINERAL COMPOSITION AND TEXTURE

Obviously it is important to know whether a producing reservoir is a sand, sandstone, limestone, dolomite, or a mixture of these. Clay, silt, bentonite, or colloidal matter, is present in appreciable quantities, may tend to clog pores near the well or to have a restricting influence on water encroachment. The average size of grains, uniformity of grain size, angularity of the sand grains,[41] average pore diameter, and the character and amount of the cementing material in sandstones influence porosity, permeability, and adsorption.

The size of the sand grains, if uniform, does not affect pore space, but must have an important influence on both the permeability and the amount of oil which will be retained by adsorption. Permeability is inversely proportional to the fourth power of the diameter of the capillary opening which is largely controlled by size of grain, although, as noted by Nutting[42] in a particularly helpful review of these factors, "Many pores become much larger than the largest grains. The average pore diameter in many sands exceeds the grain diameter." The uniformity of pore diameter as well as the size of the average pore diameter must affect especially the freedom of movement of oil globules and gas bubbles which may form in abundance when reservoir pressure becomes reduced. The temperature and character of both the oil and the advancing water, as well as the size of grain and adsorptive power of the reservoir rock, must be important factors in determining how much oil will be retained by the reservoir in spite of density of wells and production methods.

Uncemented sands may experience a rearrangement of grains as fluids are withdrawn, thereby permitting a reduction of reservoir volume by several per cent. The resulting compaction may serve as an aid to expulsion of the fluid contents of the reservoir. It does not seem probable that sands loose enough to be compacted will lack ample permeability after compaction occurs.

The purity of a limestone or dolomite reservoir is important in a consideration of the probable effectiveness of acid treatment. A knowledge of the texture or density of a limestone or dolomite, the degree of

[41] F. G. Tickell, O. E. Mechem, and R. C. McCurdy, "Some Studies on the Porosity and Permeability of Rocks," *Trans. Amer. Inst. Min. Met. Eng.* (1933), Petrol. Div., pp. 250–60.
A. F. Melcher, "Texture of Oil Sands with Relation to the Production of Oil," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 8, No. 6 (November–December, 1924), pp. 716–74.

[42] P. G. Nutting, *op. cit.*, p. 827.

cementation, and absence of clay or shale in a limestone or sandstone, should permit safer prediction as to probable effectiveness of shooting with nitroglycerine.

DEPOSITIONAL CHARACTERISTICS

Irregularities in sand bodies due to cross-bedding, channels, bars, lenses, et cetera, are well known and should receive careful attention where recognizable. Locations along these trends may safely be at greater distances than across such trends.

The presence or absence of open bedding planes, especially in limestone, may be important in estimating reservoir volume and effective drainage areas. Porosity and permeability in reef-deposited limestones, shell breccias, et cetera, may follow depositional trends.

FLUID FACTORS

GAS

The amount of free and dissolved gas has an important bearing on the total amount of energy available. Since different gas constituents contained in the oil are released from solution at different pressures and their release materially affects the energy available, viscosity of the oil, et cetera, the amount of gas and the pressure at which it is released are highly important. This information is obtained by methods such as used by Lindsly,[43] whose work showed that in the East Texas field all the dissolved gas would be retained in the oil if reservoir pressure is maintained above 755 pounds, 60 per cent if above 200 pounds. Good production practice obviously requires a maximum retention of dissolved gas in the oil while in the reservoir to avoid the formation of gas bubbles, also that the gas bubbles be prevented from increasing in size as much as possible. If gas bubbles are small or absent, less pressure differential is needed to force the oil through the interstices from one large pore space to the next, the oil is kept in a more fluid state,[44] and the energy available from the liberation and expansion of the gas is reserved for use in flowing the well.

Since high percentage recovery of oil depends chiefly on the efficient use of both the free and dissolved gas, excepting in pools under hydraulic control, the conservation of gas is of the utmost importance. Wells should, of course, be drilled at wide intervals in areas thought to be mainly gas-bearing. Where free gas occupies an appreciable part of the reservoir above the oil, good practice requires

[43] Ben E. Lindsly, *op. cit.*

[44] D. L. Katz, "Effect of Gas Liberation Upon the Properties of Crude Oil," *Oil Weekly* (October 22, 1934). Delivered before October, 1934, meeting, Petroleum Division, American Institute Mining and Metallurgical Engineers).

that either the casing or tubing-packer be placed below the free gas. A study of cores as developed in the Gulf Coast area during recent years commonly reveals the base of the gas and top of the oil sand.

The maximum use of expulsive force other than gas to attain lateral movement within the reservoir will generally require restricted production, but obviously the resulting ultimate beneficial effects must be large. The problem of an optimum gas-oil ratio to give efficient flow in the tubing is a complementary factor in actual practice.[45]

OIL

The physical properties of the oil in the reservoir seem highly important to well spacing. As previously mentioned, the successive characteristics of the oil under original and subsequent reservoir pressures may be determined within reasonable limits of accuracy.[46] No doubt this information regarding the amount of energy available from the dissolved gas and the mobility of the oil in its reservoir at various pressures will have many applications to problems of well spacing and efficient use of reservoir energy. Adoption of a certain minimum reservoir pressure to be maintained in each pool, based on results of such data, will presumably become common practice. Costs of such pressure maintenance where this can not be maintained naturally by restricted flow, or otherwise, will control to some extent the selection of a "reasonable" minimum reservoir pressure. The mobility of the oil through its reservoir during the later stages of production is a major well-spacing problem, as previously discussed under "producing permeability."

The physical expansion of the oil itself is no doubt an important item in calculating available energy,[47] especially in large pools subject to much reduction in reservoir pressure. The compressibility of oil is influenced by the amount of gas held in solution.[48] Oils vary considerably as to their adsorptive tendencies, strong alkaline water being required, excepting for light colorless oils, to release the surrounding oil films from the sand grains.[49]

[45] C. E. Reistle, Jr., and E. P. Hayes, "A Study of Subsurface Pressures and Temperatures in Flowing Wells in the East Texas Field," *U. S. Bur. Mines R. I. 3211* (May, 1933).

[46] Ben E. Lindsly, *op. cit.*
W. K. Lewis, "Properties of Hydrocarbon Mixtures as Related to Production Problems," *Trans. Amer. Inst. Min. Met. Eng.* (1930), Petrol. Div., pp. 11–33.

[47] R. J. Schilthuis and William Hurst, *op. cit.*

[48] William N. Lacy, "Application of Thermodynamic Data to Production Problems," *Amer. Petrol. Inst. Prod. Bull. 214* (Nov., 1934), Fig. 1.

[49] P. G. Nutting, "Some Geological Consequences of the Selective Adsorption of Water and Hydrocarbons by Silica and Silicates," *Econ. Geol.*, Vol. 23 (1928), p. 775.

WATER

The amount of energy which will be supplied by water advancing into the oil-bearing part of the reservoir, and the probable effectiveness in the use of this energy by the pool operators, are critical factors in planning the spacing of wells. Oil reservoirs having sufficient water drive from any cause to maintain high reservoir pressures at desired rates of production are particularly suitable for wide spacing of wells, the number of wells required being determined chiefly by structural and reservoir conditions. The percolation or surge of water caused by gravity producing regionally a hydraulic movement in the reservoir is to be expected in most reservoirs.

Also, the physical expansion of the water associated with an oil pool is now recognized as an important consideration,[50] varying in amount according to pressure differentials set up as the field is produced, volume of associated water, amount of occluded gases, et cetera. In the East Texas field, expansion of the oil and water is expected to explain the expulsion of scores of millions of barrels of oil, even though minimum allowance be made for the uncertain factor of occluded gases.

In the past, most oil fields have been produced (total volume of oil, gas, and water) at a much more rapid rate than the water could advance, and reservoir pressures have declined accordingly. Such fields as Powell, Texas, have been referred to as having no water drive. Since scores of wells pumped 100 or more barrels of water daily per well for years, it seems more plausible to say that at moderate production rates there was sufficient water drive in this field to have maintained flowing life for a reasonable number of wells for many years. Some geologists who have praised the East Texas field for its very permeable reservoir insist that it will have no appreciable water drive even when large pressure differentials are established. In opposition to this theory, it has been observed that because of some physical force, presumably water drive, the reservoir pressures in the East Texas field remain fairly constant when the production rate is limited to about 400,000 barrels per day. At this rate of flow it would take about 15 years to secure the estimated recoverable reserves in this field. If, during this period, water is to replace oil in the truncated sand members of this field, a lateral movement in each sand member, averaging about 0.15 mile per year, would be required. With an average permeability of about 2,500 millidarcys for the better grade sands and 500 millidarcys[51] for the poorer grade, there seems to

[50] R. J. Schilthuis and William Hurst, *op. cit.*

[51] G. H. Fancher, J. A. Lewis, and K. B. Barnes, *op. cit.*, p. 142. Note:—*cf.* with average permeability figures of less than 3 millidarcys for Bradford sand.

be little doubt that this rate of migration of the oil (viscosity about 2 centipoises)[52] and water in this reservoir can easily occur under the influence of present differential pressures. Plummer and Sargent[53] report that "the Woodbine water from calculations made by Slichter's method has a velocity of about .2 mile per year at the outcrop." Presumably this flow is induced by a gravitational effect of about 33 pounds per mile (75 feet of dip per mile), and might be much greater if freer outlet existed. Establishment of differential pressures somewhat greater than this will be necessary in the East Texas field if water is to advance up dip against gravity in beds dipping about 100 feet per mile and overcome resisting forces.[54] Undoubtedly the advance of water will be irregular, governed by permeability, and disproportionate for the different sand members.

It is interesting to note[55] that the average pressure differential in the East Texas field, adjusted to a −3,300-foot sea-level base, was 21 pounds per mile in the north part and for the field as a whole about 40 pounds per mile during July, 1934. A year previous, with about twice the production rate, the differential pressure on the same basis had averaged about 27 and 60 pounds per mile, respectively. Because open flowing of a well in this field is so quickly recorded by pressure gauges in wells $\frac{1}{4}$ mile or more distant, and because the field as a whole has been able to gain about 2 pounds pressure per day during periods of shut-down, it seems reasonable to believe that fluids move very freely in this reservoir; therefore, that the field has been, and will be, influenced by the enormous mass of water occupying approximately 12,000 square miles of Woodbine reservoir which lies at higher elevations across a syphon-like area about 40 miles broad. The difference in capillarity between oil and water is probably not a factor in the advance of water into oil-wet sands, according to experiments and conclusions of Dodd,[56] whose important

[52] C. E. Reistle, Jr., and E. P. Hayes, *op. cit.*, Figs. 10 and 11.

[53] F. B. Plummer and E. C. Sargent, "Underground Waters and Subsurface Temperatures of the Woodbine Sand in Northeast Texas," *Univ. Texas Bull. 3138* (October 8, 1931), pp. 57–58.

[54] Note.—As calculated by the writer, differential pressures of 5.4 pounds per mile for the oil and about 2 pounds per mile for the water for the sands having permeability of 500 millidarcys plus gravitational effect of about 44 pounds per mile should maintain fluid movement of .15 mile per year (.000766 centimeter per second) according to permeability formula, using viscosities of 2 and .74 centipoises for oil and water respectively.

[55] C. E. Reistle, Jr., "Effect of Different Production Rates on Pressure Distribution in East Texas," preprint, Fifteenth Annual Meeting, American Petroleum Institute, 1934, p. 3.

[56] Harold V. Dodd, "Some Preliminary Experiments on the Migration of Oil Up Low-Angle Dips," *Econ. Geol.*, Vol. 17 (1922), pp. 285–91.

work has apparently been overlooked by most writers on oil and water migration.

A possible factor in oil recovery about which there seems to be little or nothing published is the difference in reservoir waters in their effect on releasing the adsorbed oil films from the reservoir rock. The more concentrated solutions in deeply buried waters may assist in securing higher percentage recoveries than shallower, more dilute solutions. This action probably depends much more on the character than the amount of solids present in the water.

STRUCTURAL FACTORS

EARLY STRUCTURAL HISTORY

Since most oil and gas concentrations occur in early folds or reservoir margins, it is reasonable to conclude that most gas and oil migration takes place at a fairly early date, geologically speaking. Subsequent structural movement or regional tilting may shift to some extent the position of these accumulated fluids. It is to be expected that cementation in sandstones will be much retarded or reduced in localities where oil has been continuously present from an early date. The effect upon porosity and permeability and relation to well spacing is apparent. Likewise, in calcareous deposits early structural movements may have an important effect on the development or retention of porosity and permeability, because of exposure to weathering and ground-water leaching, or as a control for reef development.

Early folding may lead to truncation of the reservoir beds, resulting in favorable structural conditions and possible burial beneath source material, thereby aiding in the formation of oil pools. Early regional tilting of extensive reservoir beds is undoubtedly of great importance to oil accumulation, as shown by Levorsen.[57] Recognition of these early structural features has an important bearing on the choice of appropriate spacing programs suited to the various reservoir conditions, especially where reservoir bodies of variable character are present, as in the Oklahoma City field.

PRESENT STRUCTURAL CONDITIONS

The economic spacing of wells is decidedly influenced by the present structural features of the reservoir. The positions of free gas, oil, and water are commonly subject to structural control. Thick reservoirs having vertical variations require adjusted spacing arrangements on large structures. Steeply dipping reservoirs will justify closer spacing

[57] A. I. Levorsen, "Studies in Paleogeology," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 17, No. 9 (September, 1933), p. 1107.

in the direction of dip rather than in the direction of strike to avoid missing the oil-bearing area. The increased volume of reservoir space per surface acre caused by the tilted position of the reservoir warrants closer than normal spacing in areas of steep dip. Faulting must be given careful consideration, for in sandstones reservoir volume may be greatly reduced by cementation for a distance of 20 feet or more on both sides of the fault line, with the opposite effect probable in limestone and dolomite reservoirs; therefore, locations should avoid these trends in one case, and follow them in the other. Small synclinal features located well above the oil-water contact yield exceptionally long-lived wells in many places, probably because of prolonged concentration of oil drainage by gravity and less gas-bubble interference.

Variations in the character and amount of cementing material, according to position on structure, have been revealed by the study of flood waters in the Bradford field.[58] This condition may require different spacing for different zones in large fields.

Closer spacing between wells in the direction of contour lines than up or down dip and wider spacing as the gas- and water-bearing areas are approached have been advocated by writers on well spacing. Obviously, these recommendations merit careful consideration where applicable from a practical standpoint.

Oil in deeply buried fields may have decidedly different character above and below a definite subsea-level, as in Kettleman Hills, Big Lake, and the deep oil fields of the Gulf Coast area. Above a certain level, regardless of stratigraphic lines, the oil as delivered to the stock tank may be almost clear and from 50° to 60° gravity A.P.I., whereas below this critical level a dark oil of about 40° A.P.I. gravity is produced. Presumably, the former represents a gas-bearing zone containing considerable oil in gas phase held in the gas in this high-pressure and high-temperature environment. Spacing of wells in these areas of high gas-oil ratio may possibly be as wide as for gas fields, that is, 40 to 80 acres per well as a minimum.

SPACING PATTERNS

The arrangement of wells both from the standpoint of drainage and pressure maintenance deserves careful consideration. The use of either the 7-spot or 5-spot network for both efficient drainage and pressure maintenance seems advantageous over the usual square network. Theoretically, it seems good practice to drill the center well

[58] Paul D. Torrey, "Origin, Migration, and Accumulation of Petroleum and Natural Gas in Pennsylvania," *Problems of Petroleum Geology* (Amer. Assoc. Petrol. Geol., 1934), pp. 479–83.

first with the expectation that its pressures will be lowest when gas injection begins. In practice, other wells may prove better suited to this purpose.

Doubtless the effective drainage areas of wells should overlap each other to some extent. Pressure maintenance should aid late wells in establishing the drainage channels needed for efficient recovery in some types of reservoirs and thereby permit abnormally wide spacing experiments, to be judged by recovery results.

CONTINUED ADVANCEMENT IN DRILLING AND PRODUCTION TECHNIQUE PROBABLE

Since drilling and production technique have shown remarkable progress in recent years, it is reasonable to assume that recovery methods will become more and more efficient during future years, and, therefore, that the trend will be toward wider and wider spacing where reservoir conditions permit.

Presumably, only a good beginning has been made in such important matters as pressure maintenance, repressuring by gas or air, flooding with water, acid treatment of limestone and dolomite reservoirs, chemical treatment of sandstones, shooting, directional and multiple drilling, lateral drilling, mining, efficient spacing patterns, efficient flowing and lifting equipment, and perhaps numerous other recovery methods as yet unthought of, all of which seem to encourage and justify the present trend toward wider spacing of wells.

CONCLUSION

The attainment of greater efficiency in the production of oil is obviously of great import to both the producers and consumers of oil. No doubt one of the most important factors involved is the economic spacing of wells. This article has been prepared in the hope that increased study will be given this subject, and that contributions by both petroleum geologists and petroleum engineers to the Association *Bulletin* on this and allied subjects will become more numerous.

It is evident that from a practical standpoint spacing intervals are not subject to precise calculation. The variables involved include matters of economics, ownership, engineering, and geology, many of which are beyond control and not subject to exact prediction. However, decision must be made, and with as much exactitude as possible in so important a matter. In practice it is suggested that the well-spacing problem be approached by some such procedure as the following.

1. Classify the reservoir according to its probable control, namely

hydraulic, volumetric, or "capillary," or, in other words, the probable relation of energy available to energy required for high percentage recovery.

2. Estimate the effective drainage area under ideal conditions of wells drilled under this type of control and conditions which will obtain, such as depth, character of oil and reservoir ("producing permeability"), et cetera, for example, one well per 80, 40, or 20 acres, respectively, for hydraulic, volumetric, or "capillary" control.

3. Estimate to what extent fixed physical factors, such as lenticularity of reservoir or structural conditions, limit or require modification of this maximum spacing.

4. Consider probable effect of the operating practices which will be followed. These will affect many of the factors involved.

5. Consider what adjustment, if any, is needed because of ownership, economics, or proration.

6. Estimate the probable net operating return per acre as a possible factor, either to decrease or increase the normal density of wells.

7. Compare alternative spacing plans as to added costs and additional net returns probable from closer spacing and greater number of wells.

8. Adopt the widest and most flexible spacing plan feasible, with provision for drilling additional wells if needed for high percentage recovery.

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EXTRATERRESTRIAL HYDROCARBONS AND PETROLEUM GENESIS[1]

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Golden, Colorado

ABSTRACT

Recent spectroscopic examinations of the atmospheres of the major planets, Jupiter, Saturn, Uranus, and Neptune, by Adel and Slipher, have revealed the fact that methane is the major constituent. Furthermore, they state that "the unanchored motion of Jupiter's Great Red Spot suggests that it is an island of solid hydrocarbon or ammonia floating in a vast hydrocarbon ocean as extensive as the planet's surface itself." No definite data are available relative to the composition of the supposed hydrocarbon ocean.

By reasoning from analogy, it is suggested that hydrocarbons may have been present in the primordial earth, though it is admitted that convincing evidence has not yet been presented to prove that commercial accumulations of petroleum and natural gas have originated from such a source.

INTRODUCTION

The question of petroleum genesis is, and probably will remain for a long period, one of the great unsolved problems of geology. The subject is of such practical importance that all evidence bearing on it even remotely should be brought to the attention of workers in this field. The theories of origin of petroleum and natural gas are too well known to warrant an extensive review here. Suffice it to say that the organic theories have received the most attention and are widely held to-day, though certain adherents of the inorganic theories have held to their views tenaciously in late years in spite of the fact that the evidence appears to be preponderantly against them. Within the past year some very interesting data with a possible bearing on the inorganic theories have been contributed by astronomers.

EXTRATERRESTRIAL HYDROCARBONS

Adel and Slipher,[4] of the University of Michigan and Lowell Observatory, in an extremely interesting and enlightening article based on extensive spectroscopic investigations of the gaseous envelopes of the major planets of our solar system, Jupiter, Saturn, Uranus, and

[1] Read before the Association at the Wichita meeting, March 23, 1935. Manuscript received, March 15, 1935.

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[3] Instructor in geology, Colorado School of Mines.

[4] Arthur Adel and V. M. Slipher, "The Constitution of the Atmospheres of the Giant Planets," *Physical Review*, Vol. 46 (1934), pp. 902–06.

Neptune, have revealed the fact that methane is the major constituent of their atmospheres. More recently, Henry Norris Russel,[5] research professor of astronomy at Princeton University, has reviewed the evidence bearing on the atmospheres of the planets and has accepted without question the observations of Adel and Slipher.

The latter investigators[6] say:

Whereas of the small planets Venus, Earth and Mars possess appreciable atmospheres, each of the large ones is surrounded by a vast one as is evidenced by the high albedos and rich solar spectra of the major planets.

They summarize their data as follows.[7]

An analysis is made of the absorption spectra of the major planets Jupiter, Saturn, Uranus, Neptune. Approximately forty of the rotation-vibration bands are identified as due to absorption by the methane molecule and are correlated in terms of the fundamental frequencies of vibration. It appears that methane is the major constituent of the atmospheres of these distant bodies, the quantity in the absorbing strata increasing markedly from Saturn to Neptune. The absence of any appreciable amount of other hydrocarbon material is demonstrated.

In regard to the lack of other gaseous hydrocarbons they point out that practically the only ones that need to be considered are ethane, ethylene, and acetylene, for only these could exist in the gaseous state at the low temperatures which prevail (below $-150°$ C.) as determined by radiometric measures.

As Russel[8] has pointed out, these higher gaseous hydrocarbons all have bands in places clear of disturbance by methane, and the failure to find evidence of the existence of them is significant. It should be noted here that R. Wildt of Göttingen has demonstrated the existence of small amounts of ammonia in the atmospheres of Jupiter and Saturn. Concerning the amount of methane in the atmospheres of the outermost planets, Russel[9] says:

From the published data it appears that the amount of methane above the visible surface of Jupiter is of the order of one mile-atmosphere.[10] There must be much more on Uranus, and especially on Neptune; but we cannot yet estimate its amount.

It is of especial interest to note that Jupiter may possess a universal

[5] Henry Norris Russel, "The Atmospheres of the Planets," *Science* (New Ser.), Vol. 81 (1930), pp. 1–9.

[6] *Op. cit.*, p. 902.

[7] *Idem*

[8] *Op. cit.*, p. 5.

[9] *Idem*

[10] One mile-atmosphere is equivalent to a layer one mile thick at standard atmospheric pressure and temperature.

hydrocarbon ocean in addition to its gaseous hydrocarbon envelope. To quote Adel and Slipher:[11]

> The unanchored motion of Jupiter's Great Red Spot suggests that it is an island of solid hydrocarbon or ammonia floating in a vast hydrocarbon ocean as extensive as the planet's surface itself.

Even the solid outer parts of the major planets may contain appreciable quantities of hydrocarbons. The densities of these planets range from 1.6 for Neptune to 0.7 for Saturn. Russel[12] says:

> From the ellipticity of a planet and the change in its satellites' orbits caused by the attraction of its equatorial bulge, information may be obtained regarding the degree to which the density increases towards its center. Applying this to Jupiter and Saturn, Jeffreys concludes that they contain cores of rock and metal, like the inner planets, surrounded by vast shells of ice—frozen oceans thousands of miles deep—and above this, again, atmospheres of great extent. Throughout most of the atmosphere, the pressure must be so great that the gas is reduced to a density as great as it would have if liquefied, or even solidified, by cooling. . . .
>
> Now this outer layer is of low density—less than 0.78 for Jupiter and 0.41 for Saturn—according to Wildt's calculations. This excludes all but a few possible constituents. Frozen oxygen has a density of 1.45, nitrogen 1.02, ammonia 0.82. Only hydrocarbons (methane 0.42, ethane 0.55), helium (0.19), and hydrogen (0.08) come within the limits even for Jupiter. We can therefore conclude from considerations of densities alone, that the outer parts of Jupiter probably, and of Saturn certainly, contain great quantities of free hydrogen or helium. Uranus and Neptune are similar to Jupiter.

From the information available it seems that the author might have considered the solid hydrocarbons of low densities as constituting an important part of the outer shells of the major planets as well as free hydrogen and helium.

POSSIBLE BEARING ON ORIGIN OF TERRESTRIAL HYDROCARBONS

Inasmuch as it is generally conceded by astronomers that the planets of our solar system are closely related in origin and that they are similar in constitution, due allowances being made for variations in the proportions of the various components, one can not fail to conclude that hydrocarbons may have been represented in the primordial earth. As to whether important oil and gas pools may have originated from this source, the writers are not prepared to say. The purpose of this paper is to bring the data now well known to astronomers to the attention of petroleum geologists to whom the responsibility for the ultimate solution of the problem of petroleum genesis belongs.

[11] *Op. cit.*, p. 906.

[12] *Op. cit.*, p. 6.

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GEOLOGICAL NOTES

SIMPLIFICATION OF THE JOHN L. RICH DIP CONSTRUCTION

It seems certain that the following simple method of application of the elegant construction given by John L. Rich in the January, 1932, number of this *Bulletin*[1] must have occurred to many users of the construction, and this description may be superfluous.

The following modifications entirely eliminate geometrical constructions, and make it possible to read off the values directly. The accessories required are a circular protractor engraved on paper, a set square, and a ruler with one edge graduated with *any* convenient scale. The nature of this scale is immaterial, but millimeters are about the most convenient for most purposes. As will be shown later, even this equipment may be reduced.

The application is as follows.

Taking the example worked out by Rich in the original paper, namely, component, down S. 30° W., 8 inches in 30 feet; component, down S. 15° E., $1\frac{1}{2}$ feet in 120 feet, converts slopes to fractions with unit numerators, giving dips of 1 in 45, and 1 in 80, respectively.

Lay the ruler on the protractor with its edge passing through the center and the S. 30° W. point, and place a pencil dot at a distance of 45 units of length from the center.

Proceed similarly with the other component. The direction determined by these two points is the direction of strike.

Lay the ruler with its edge passing through the two dots, and apply to it one of the rectangular sides of the set square, and slide it along the ruler until the other rectangular side intersects the center of the protractor. Hold the square in position, and measure along the side passing through the center the distance from that point to the strike-line edge of the square. This distance gives the denominator of the fraction with unit numerator corresponding with the amount of the true dip required. The direction of the true dip is given by the graduation on the protractor intersected by the edge of the ruler when applied to the dip-line edge of the protractor (Fig. 1).

Since the only marks made on the paper are two light dots for

[1] John L. Rich, "Simple Graphical Method for Determining True Dip from Two Components and for Constructing Contoured Structural Maps from Dip Observations," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 1 (January, 1932), p. 92.

each measurement, little erasure is required, confusion is impossible, and the protractor is practically indestructible.

An exceedingly simple extension provides for the direct application of the method to steeper dips, more conveniently measured with a clinometer and expressed in degrees.

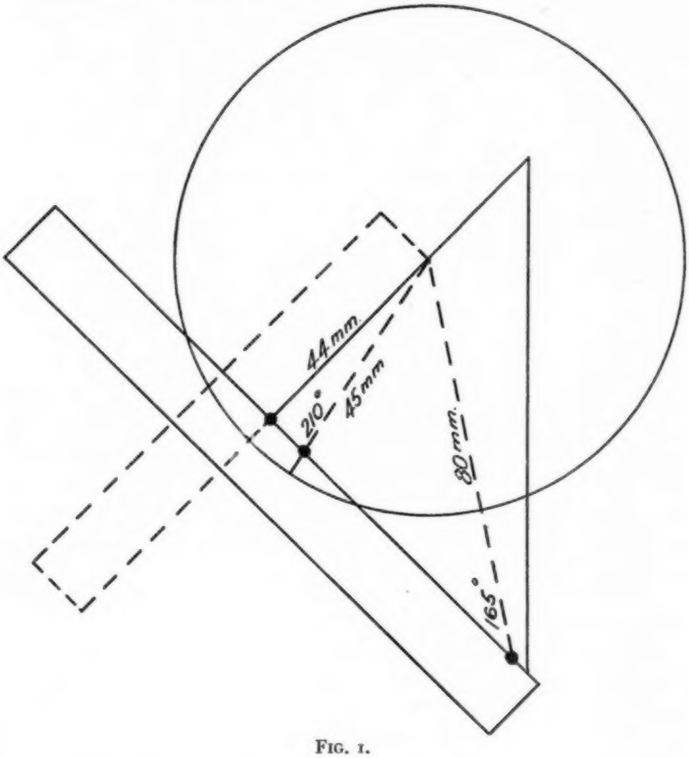

FIG. 1.

With the 0°–180° line of the protractor vertical (Fig. 2), draw the horizontal diameter of the protractor. To the right of the center O choose *any* convenient point A. If this distance is made 10 units of length of any kind, the numerical ratio for the dip slope can be read directly by simple measurement. For the immediate purpose of determining true dip direction and amount this is unnecessary, and arbitrary lengths can be used. Through A draw a vertical line AB of indefinite length.

To convert the first angle of apparent dip, say, S. 15° E. at 21°, the corresponding length required in the construction, lay the straight edge from the center O to the graduation (here 21°) corresponding

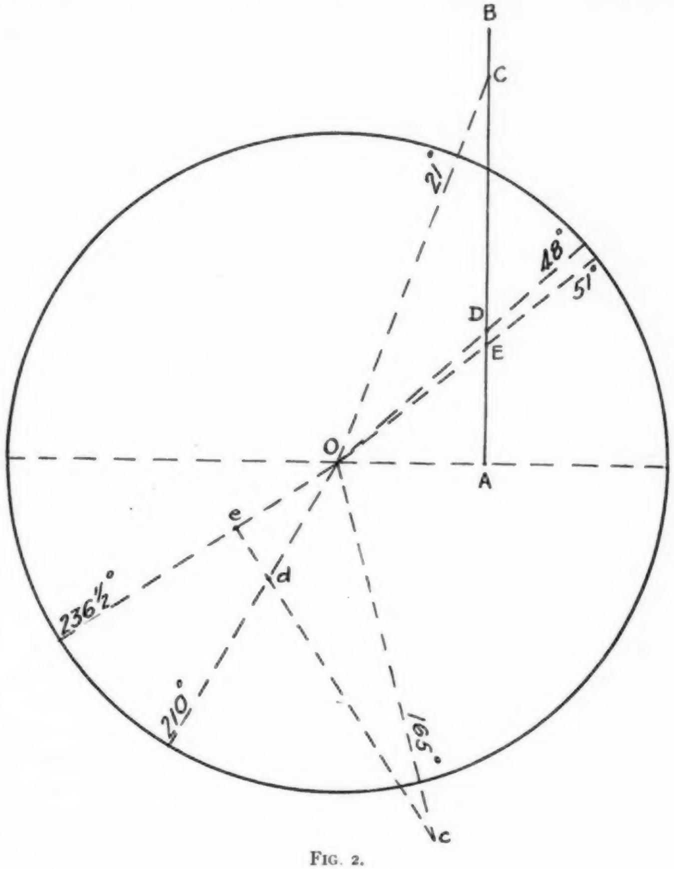

FIG. 2.

with the angular value of the dip. Let this intersect the vertical line *AB* in *C*. Proceed similarly with the second apparent dip, say, S. 30° W. at 48°, giving an intersection *D* on the vertical.

On the direction S. 15° E., dot a point *c* such that the length $Oc = AC$, and on the direction S. 30° W., dot a point *d* so that $Od = AD$. Apply ruler and set square as before, and note the distance *Oe* from

the center to the strike-line edge of the set-square. The dip-line edge of the set square passes through the graduation on the limb of the protractor corresponding with the true dip direction, in this case S. $43\frac{1}{2}°$ W. On AB mark off a length $AE=Oe$. The line OE, produced if necessary, cuts the limb of the protractor at the graduation indicating the amount of true dip, here 51°.

Though in this description the steps are indicated in the form of a construction, no actual construction is needed other than the drawing of the vertical line. The points, C, c, D, d, E, e, are simply dotted on the paper, and directions are measured with the straight edge. It is necessary to have some means of transferring the various lengths, and dividers are the most convenient for the purpose. It should be noted that only absolute lengths on the paper are required, and no system of units is essential. Of course, for any one operation the same vertical line must be used, but, for different combinations, different verticals may be taken. If dips are low, OA should be large; if the dips are high, OA should be small.

The reasoning is perfectly obvious. OA being constant for any one operation, ratios such as $OA:AC$ are the tangents of the corresponding dip angles with common numerators, whence the Rich construction immediately follows.

Still greater simplification in operation is attained by substituting a rectangular cross drawn on a transparent base such as tracing linen or celluloid for set square and ruler. One arm of this cross can be graduated with any convenient length scale. A small hole at the center permits the dotting of points on the protractor, over which the cross is moved as required.

Thus, in the first example, the graduated arm of the cross is laid in the S. 30° W. position, with the 45 unit graduation at the center of the protractor (Fig. 3), and a dot made through the hole. This is repeated for the second component. The ungraduated arm of the cross is made to pass through the two dots and the graduated arm is brought to the center of the protractor, when the direction of true dip can be read off on the circumference, and the gradient denominator can be read on the graduated arm.

Obviously, the arms of the cross can be graduated with different scales to provide for different cases, the same units being maintained during any one operation. In actual practice scales of millimeters and of inches and tenths cover all probable cases. If the dip of a geological datum surface is lower than about 1 in 120, the minor irregularities inseparable from the nature of the surface introduce sources of error large in comparison with the magnitudes involved, and only a fic-

titious accuracy is obtained. At the other extreme, dips as steep as, say, 1 in 5, are best measured and expressed in degrees, and fall within the scope of the second modification.

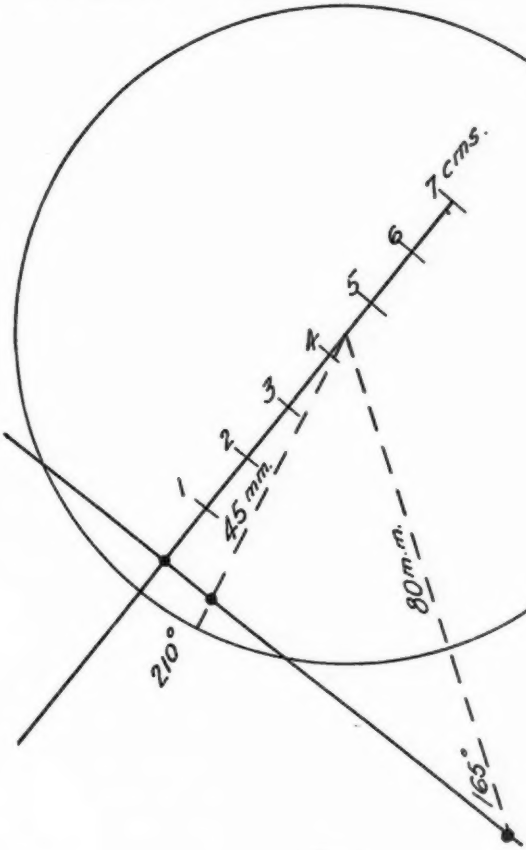

FIG. 3

APPARENT DIPS IN CONSTRUCTION OF GEOLOGICAL SECTIONS

The very frequent case of determination of the dips which have to be plotted in the construction from a plan of a geological section can be worked out by the methods given in the preceding paragraphs. In most instances where any considerable amount of such work is to be done, the draftsman will usually have at his disposal one of the

many apparent dip diagrams or tables, and construction will be superfluous and time-consuming. In cases where it is necessary to work out such apparent dips, however, these simplified procedures save considerable time.

Thus (Fig. 2), if the true dip is $43\frac{1}{2}°$ W. at 51° and the direction of section is S. 30° W., obtain the point *E* on *AB* corresponding with the amount of true dip. Measure off *Oe* on the direction of true dip, and with the aid of set square and ruler, determine the point *d* on the radius of the protractor corresponding with the direction of section. Measure *Od* and transfer to *AB*, giving *D*, and hence determine the value of the apparent dip to be plotted.

Since, in this problem, the direction of the apparent dip is constant, and it is the directions of the true dips which are variable, the line representing direction of section on the protractor is a fixed one. In many, probably in most, instances, it is more convenient to measure on the plan the actual angle between the directions of true dip and the direction of the section line, rather than to measure the actual directions of true dip. When this is so, it is simpler to regard the vertical diameter of the protractor as the section line, and to determine the various *e*-points on the approximate radii of the protractor corresponding with the angles of divergence (direction angles) between true dips and section direction. The graduation of the fixed radius representing section direction in suitable units facilitates the transference of lengths to the *AB* line, but is not an essential feature of the method.

W. G. Woolnough

Commonwealth of Australia
Dept. Interior, Canberra, F. C. T.
February 25, 1935

GRAPHIC METHOD FOR DETERMINATION OF TRUE DIP IN PITS

A number of methods may be employed to determine the true dip of a stratum, given the angle and direction of the apparent dips on the adjacent walls of a pit. The following graphic method for the determination of true dip was designed by Charles Wells after the writer had explained the geological principles involved. It is particularly useful where dips are low and where it is not possible to take a direct reading on a resistant bed.

The angle and direction of apparent dips are read on adjacent sides of the pit. On the chart (Fig. 1), a scale is so placed that it joins

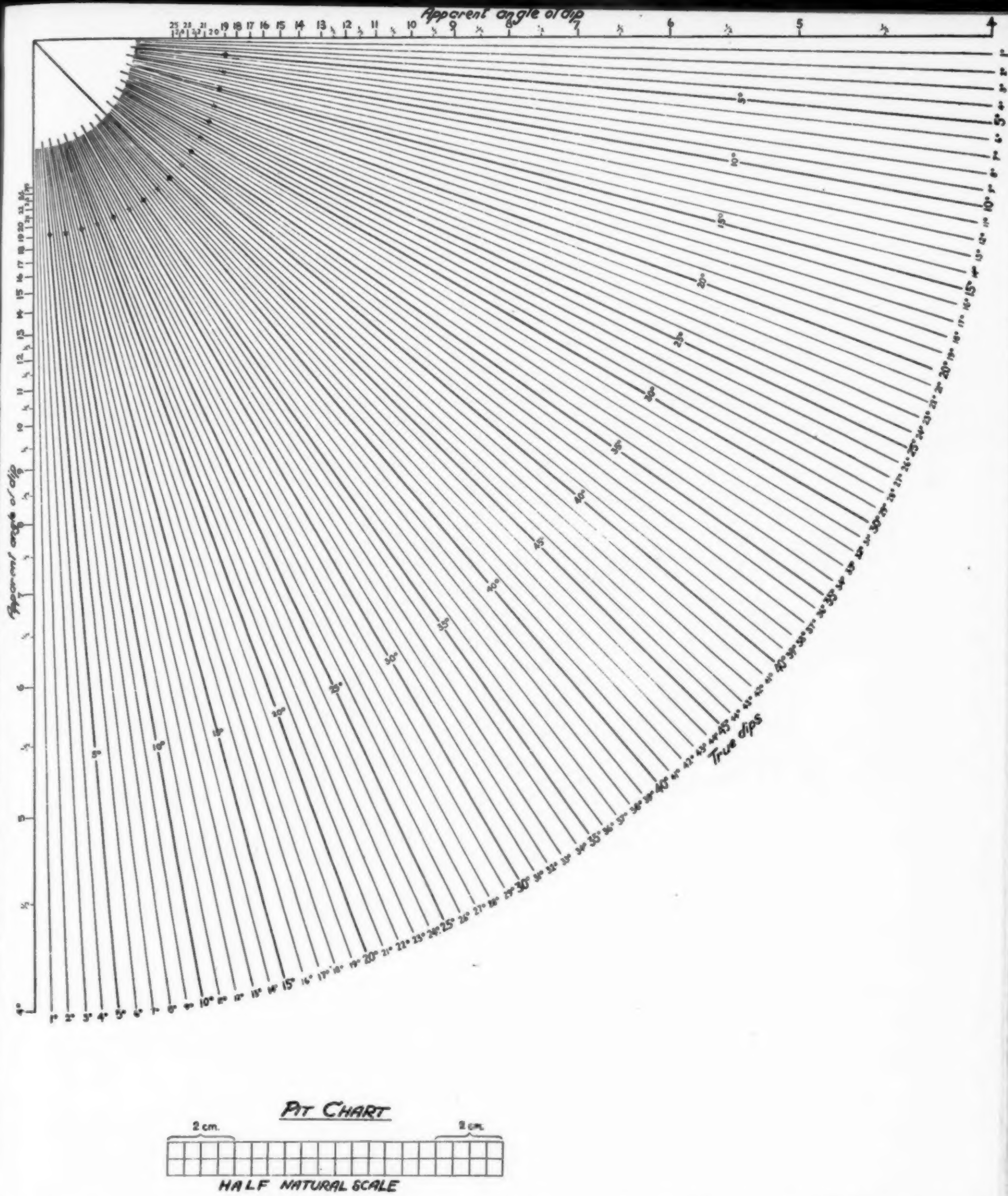

FIG. 1. *Editorial note by John L. Rich.*—Inasmuch as the chart accompanying the geological note by Mr. Weisbord ha been reduced one half for publication, the scale has been changed, and anyone using the method described must construc his own chart on a larger scale. The author omits giving directions for doing this.

As to the principle involved in the construction: imagine two horizontal planes separated by any convenient vertic interval (the author used 2 centimeters). Then, for the graduations representing "apparent angle of dip" the formula

$b=\dfrac{a}{\tan \alpha}$, where α is angle of apparent dip
a is vertical interval between planes
b is horizontal distance from point of origin

In use of the chart, the position of the strip scale, when one of the cross lines on it has been brought into coinciden with the radiating angle lines, represents the strike. Bringing the cross lines on the movable scale into coincidence with o of the radiating angle lines is merely a graphical method of erecting a perpendicular from the movable scale to the point origin; and counting the number of degrees subtended on the movable scale by a distance equal to the interval, a, betwe the planes is equivalent to rotating the true-dip triangle up into the horizontal.

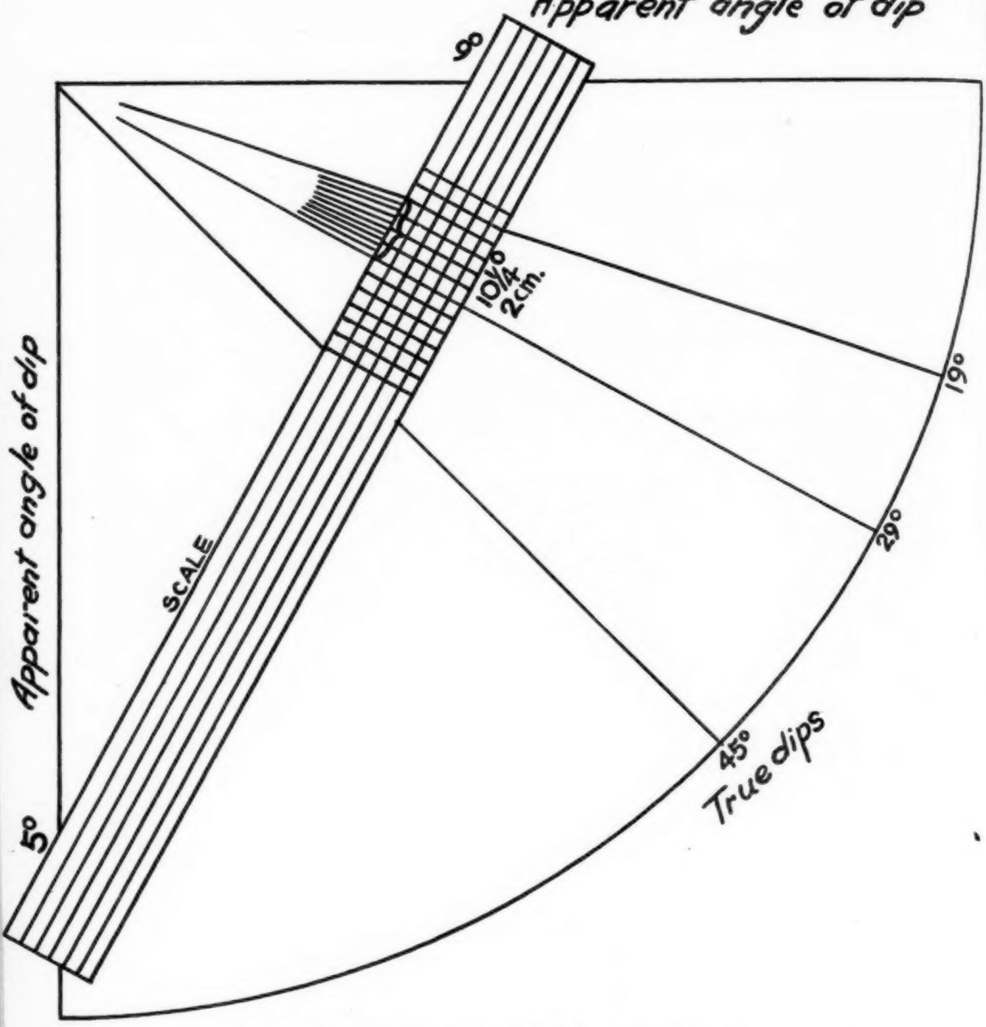

FIG. 2.—Pit chart, one half natural size, showing method of use.

the apparent angle of dip of one side of the pit with the angle of dip of the adjacent side. Thus if the apparent dip on one wall is 5° N. 30° E., and the apparent dip of the adjacent wall is 9° S. 60° E., the scale would be placed at 5° on one column of the chart and 9° on the other column (Fig. 2). The scale is moved between these points until one of the radiating lines on the protractor coincides, and is aligned with one of the lines of the scale. The number of radiating lines of the protractor which fits into 2 centimeters (on this particular scale) starting from the line of coincidence, represents the amount of dip—in this example 10¼°. By following the line of coincidence down the protractor, the angle to be *added* to the direction of *greater* dip is found to be 29°. By adding 29° to S. 60° E., the direction of true dip is found to be S. 89° E. The addition must always be *toward* the lesser angle of dip.

The chart presented here has been so designed that dips between 4° and 20° may be read. When used in its natural size, the unit of measurement of the scale is 2 centimeters. A convenient scale may be cut from a strip of cross-section paper long enough to span the chart and wide enough (2 centimeters or so) to be able to align one of the radiating lines of the protractor with one of the vertical lines of the scale. For precise readings the walls of the pit should be approximately at right angles to each other.

NORMAN E. WEISBORD

TARTAGEL, CAMPAMENTO CENTRAL
FCCNA, ARGENTINA
March 10, 1935

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 19, NO. 6 (JUNE, 1935), PP. 912-915

DISCUSSION

DEMISE OF "BRADFORDIAN SERIES"

The strata in the northwestern counties of Pennsylvania which were originally included[1] in the Bradfordian series appear quite definitely not to bridge gradationally the Devonian and Mississippian systems as has long been supposed by many workers[2]; nor are they wholly Devonian[3] or entirely Mississippian,[4] as various papers and textbooks have urged. The gradational concept, though erroneous, most closely approximates actual conditions. A minor disconformity separates the Knapp beds of the "Bradfordian," which are of Mississippian age, from the antecedent Conewango beds of Devonian age. The faunas of the two divisions of the "Bradfordian series" offer very cogent arguments for such determinations of age. In view of this condition it has been urged[5] that the usage of the term Bradfordian be discontinued and that two acceptable series names be used for its components. The name Oil Lake series was suggested for the Mississippian strata and Conewango for the uppermost Devonian sequence.[6]

The stratigraphic members of the Knapp sequence have been assigned to the Cussewago monothem[7] of the Oil Lake series. The lowest member of the monothem, the Kushequa (Knapp) shale, wedges out in an easterly direction beneath the Pottsville disconformity in the eastern part of McKean County, not far east of Smethport, Pennsylvania. The identification of these beds as Mississippian gives this system somewhat more extensive distribution than was recently indicated for it in this region.[8] A study of the fossil faunas of the Knapp sequence clearly substantiates this age determination to the writer's mind. *Eumetria scansa*, three species of *Syringothyris* (in the strict sense), several species of the highly typical lower Carboniferous gastropod *Igoceras*, as well as the interesting echinoid genera *Lepidesthes*, and *Hyattechinus*, and also several interesting crinoids would seem clearly to bespeak the Mississippian age of the Cussewago monothem. None of these fossils is known from the underlying Conewango series, or, to the writer's knowledge, from the Devonian elsewhere. Associated with the Mississippian genera is an ap-

[1] G. H. Girty, *Science*, Vol. 19 (1904), pp. 24–25.

[2] Notably, J. M. Clarke, *New York State Mus. Bull. 69* (1903), pp. 996–99.

[3] G. H. Girty (in Bailey Willis), *U. S. Geol. Survey Prof. Paper 171* (1912), p. 421.

[4] Most notable are: *New York State Mus. Handbook 19* (1912), p. 87; *ibid., Handbook 10* (1931), Pt. 2, pp. 418–28; *Internat. Geol. Cong. Guidebook 4*, Excur. A4 (1932), table, opp. p. 6.

[5] K. E. Caster, *Bull. Amer. Paleon.*, Vol. 21 (1934), pp. 1–185.

[6] This solution, which had been outlined in personal correspondence prior to publication of Caster's paper, was apparently accepted by G. H. Chadwick in 1933 (*Pan. Amer. Geol.*, Vol. 60, p. 197, 1933), but has been recently rejected (*Amer. Jour. Sci.*, Vol. 29, p. 136, 1935), for unexpressed reasons.

[7] Term: see, Caster, *op. cit.*, p. 18.

[8] G. H. Chadwick, *op. cit.* (1935), p. 135.

proximately equal number of "Waagen mutants" of Conewango species. This close affinity between faunas might be expected in view of the evidence for only a very brief hiatus between the Oil Lake series and the Conewango. However, in the writer's experience, virtually none of the Conewango species occurs morphologically unaltered in the Knapp sequence. To be sure, if reliance is placed on the older published lists of fossils which were based on less definitive studies, this condition will not appear.[8a] Re-examination of a large part of the material on which published lists were based has tended largely to refute them. At this point a word of caution must be offered relative to the oft-cited[9] occurrence of *Syringothyris* in the Chagrin sequence of Ohio. A form described by Prosser as *S. chemungensis* occurs at the horizon of the Panama conglomerate at the base of the Conewango.[10] This fossil loses its momentum as a proof of the unreliability of the genus *Syringothyris* when it is recognized that "*Syringothyris*" *chemungensis* is in reality the genotype (that is, presumably will be) of an as yet undescribed syrinx-bearing genus of spiriferoid brachiopod. The range of this syrinx-bearing stock seems to be wholly Devonian, and apparently it is not in the direct line of descent of the Mississippian *Syringothyris*.

In the upper part of the Oil Lake series, in western Pennsylvania, the Corry sandstone (possibly of Berea age) occurs. The fauna of the Corry is of a characteristic Kinderhook aspect. Important among a large number of indicial fossils in the sandstone are representatives of the *Productus ovatus* species-group, of *Paraphorhynchus, Shumardella,*[11] and *Chonopectus*. There also occur in the Corry several mutants of the Mississippian species which first appear in the Knapp sequence. So far as known, not one species occurs in both the Conewango and the Corry. Reports which would seem to contradict this statement appear to have been founded on erroneous correlations. The opinion is recently expressed[12] that the entire Bradfordian may be of Devonian age and that possibly not only the Cussewago monothem, but also the Corry sandstone ought to be included in the Bradfordian. This even surpasses the all-inclusiveness of the original Bradfordian and well illustrates the error into which lists of fossils that are separated from the specimens on which they are based may lead even the most careful stratigrapher. The Oil Lake series is, at least to the writer, clearly of Mississippian age.

The many current references of the "Bradfordian series" wholly to the Mississippian are based, it seems, on the erroneous assumption of ubiquity in the "series" of the remarkable Mississippian genera which are restricted to the upper part of the terrane. The Conewango fauna is characterized by several genera which make their first appearance in the biologic record at its base. In all respects, however, it appears that the Conewango fauna is de-

[8a] This statement is largely true for the stratigraphically very helpful, but by no means systematically final, Upper Devonian faunal lists which are incorporated in the excellent paper by Mr. G. H. Chadwick, cited under footnote 18 of this discussion, the taxonomy of which is apparently based almost wholly on commendably exhaustive literature studies rather than on a systematic re-examination of the paleontologic materials. (K.E.C. May 28, 1935.)

[9] Most recently cited by G. H. Chadwick, *op. cit.* (1935), p. 142.

[10] Correlation: see Caster, *op. cit.* (1934), p. 80.

[11] See Charles Butts, *in litt.* (1935).

[12] G. H. Chadwick, *op. cit.*, p. 136.

rived from the more or less indigenous subjacent Upper Devonian faunas. This is clearly not the case for the Cussewago faunas. The hiatus at the bottom of the Conewango, and the faunal hiatus likewise seem at the present time to be comparable to that between the other series of the Upper Devonian. There is a current tendency[13] to minimize the faunal change from the Chadakoin to the Conewango. At the present stage of his faunal studies, the writer feels that the break between the Conewango and Chadakoin is of serial importance, and that the next lower hiatus of comparable importance is that between like facies of the true Chemung and Enfield. It is true that there are well marked faunal changes from one division (stage or "group") of the Chautauquan to another. However, in the writer's limited experience, these faunal transitions are less striking when similar facies of the vertically adjacent stages are compared.

Even as the limit of the Mississippian system in Pennsylvania has been misjudged, so also, it appears, has the distribution of the Conewango been mistakenly curtailed, especially in southwestern Pennsylvania. The uppermost Devonian strata which occur on the Chestnut Ridge anticlinal inlier of the Allegany plateau in Fayette County were originally recorded by J. J. Stevenson as Chemung. Later, Charles Butts determined them to be of Conewango age.[14] More recently these strata were reëxamined and the faunal lists augmented by Bradford Willard.[15] He concluded that the strata were correlates of the Lower Chemung of New York (Cayuta). In a current paper by G. H. Chadwick[16] the strata were stated to be definitely of post-Chemung age (Canadaway). This determination was based largely on the published lists of Stevenson and Willard and faunal observations in the study of the stratigraphy of New York. During the spring of 1934 the writer had the good fortune to make a fossil collection from the locality the age of whose strata is under dispute. Among a numerous fauna were found specimens of *Pararca* and *Ptychopteria* (definitely not *Oleanella*) and variants of the *Spirifer disjunctus* species-group. These genera and variants (one of which is occasionally mistaken for the Chemung *Spirifer mesistrialis*) are known only from the Conewango or above. This additional faunal evidence would seem to bear out Mr. Butts's diagnosis.

This note is written in no spirit of controversy, but rather as a statement of honest conviction, based, it is believed, on adequate evidence. The recent paper by Chadwick[17] dealing with the highly important question of "What is Pocono?" is a model of conciseness and clarity of presentation. His Pocono arguments are well taken. With his views on sub-Conewango stratigraphy in New York and Pennsylvania the writer is almost wholly in accord. However, the writer does regret and take exception to the seemingly erroneous concepts of Conewango and Oil Lake ("Bradfordian") stratigraphy and paleontology which were included in the recesses of Mr. Chadwick's able paper.

DEPARTMENT OF GEOLOGY
CORNELL UNIVERSITY
February 22, 1935

KENNETH E. CASTER

[13] *Ibid.*, pp. 136–37.

[14] Charles Butts, *Pennsylvania Topog. and Geol. Survey Rept.* 1906–08 (1908), p. 198.

[15] B. Willard, *Proc. Pennsylvania Acad. Sci.*, Vol. 7 (1933), pp. 1–12.

[16] G. H. Chadwick, *op. cit.*, pp. 140–42.

[17] *Idem, Amer. Jour. Sci.*, Vol. 29 (1935), pp. 133–43.

In the paper on the "Bradford Oil Field," by Newby, Torrey, Fettke, and Panyity, in *Structure of Typical American Oil Fields*, Vol. II, pages 412 and 413, the early Mississippian age of the Knapp sandstone was noted. The collections of fossils upon which this determination of age was established were made by Charles Butts of the United States National Museum and the writer during the spring of 1925. At that time Butts appeared to be completely satisfied that the Knapp was Mississippian in age and that the formation was older than Pocono; the upper part being presumably Burlington or New Providence in age and the lower part Kinderhook in age. The fact that Caster has found a fauna in the Corry sandstone almost identical with that collected and identified by Butts and the writer from the Knapp in Cattaraugus County, New York, and McKean County, Pennsylvania, is most noteworthy and is indicative of a much more continuous connection between deposition of the early Mississippian rocks between the Mississippi Valley and northwestern Pennsylvania.

The reason for separating the Oswayo beds from the Cattaraugus in the McKean County paper (Caster's Conewango) is based both on lithologic character and fossil evidence. The Oswayo of southern Cattaraugus County is characterized by an abundance of the invertebrate *Camarotoechia allegania*, which, as far as the writer knows, is not found in the Cattaraugus beds. The separation of these two units in southern Cattaraugus County, therefore, appears to be justified.

PAUL D. TORREY

BRADFORD, PENNSYLVANIA
February, 1935

At least partial reply to some of the questions raised by Dr. Caster in this manuscript will be found in the two subsequently published papers by Chadwick in the *Bulletin* of the Geological Society of America.[18] Our differences of view revolve around not so much the field facts and the correlations as matters of opinion and interpretation. It may, therefore, be desirable here to restate briefly the critical consideration that led me, on second thought, to reoppose his claim of Mississippian age for the Cussewago-"Berea" or Oil Lake beds. It seems to me incredible that *Spirifer disjunctus*, persisting abundantly throughout these disputed strata, should be wholly absent from undoubted Mississippian strata of precisely similar facies just over in the next state (Ohio), if these are really Mississippian beds of even later age than those, as Caster claims. The Bedford is below the true Berea, and nothing ever called "*Spirifer disjunctus*" is found in the now well explored Bedford fauna. It seems necessary, therefore, to reject the "Berea" age of the beds in northwest Pennsylvania holding *S. disjunctus*, and to make them older than the Bedford. Structurally they are still a part of the upper Devonian delta deposits, though naturally, as the latest upper Devonian, they contain an increasing Mississippian element. At this point, opinions will, of course, diverge.

GEORGE H. CHADWICK

CATSKILL, NEW YORK
May 5, 1935

[18] George Halcott Chadwick, "Faunal Differentiation in the Upper Devonian," *Bull. Geol. Soc. America*, Vol. 46, No. 2 (February 28, 1935), pp. 305–42.

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VOL. 19, NO. 6 (JUNE, 1935), PP. 916-919

REVIEWS AND NEW PUBLICATIONS

* Subjects indicated by asterisk are in the Association library and available to members and associates. List of technical periodicals available for loan to members and associates was published in the *Bulletin*, Vol. 18, No. 9 (September, 1934), pp. 1215–17.

RECENT PUBLICATIONS

BRAZIL

**Mapa Geologico do Brasil Meridional* (Map of the Geology of Southern Brazil with Special Reference to the Gondwana Formations), compiled by Victor Oppenheim. 2 sheets in colors, each about 35×18 inches. Scale, 1:2,750,000. Requests for copies of this map, which will be available in limited numbers, and for copies of the text prepared by Oppenheim, should be addressed to the director of the Serviço de Fomento da Produção Mineral, Avenida Pasteur 404, Rio de Janeiro, Brazil.

CALIFORNIA

*"Mt. Poso Oil Field," by Alex Diepenbrock. *California Oil Fields* (Dept. Natural Resources, Div. Oil and Gas, San Francisco), Vol. 19, No. 2 (dated, October, November, December, 1933; published, 1935), pp. 5–35; 8 pls.

CANADA

"Geology of Central Alberta," by John A. Allen and Ralph L. Rutherford. *Research Council of Alberta* (Univ. of Alberta, Edmonton) *Rept. 30* (1934). 40 pp., 2 pls., pocket map.

COLORADO, UTAH, WYOMING

"The Recognizable Species of the Green River Flora," by R. W. Brown. *U. S. Geol. Survey Prof. Paper 185-C* (1935), pp. 45–77, Pls. 8–15. For sale by Supt. Documents, Govt. Printing Office, Washington, D. C. Price, $0.10.

EASTERN MEDITERRANEAN

* "Premiéres recherches sur les hydrocarbures minéraux dans les états du Levant sous mandat Français" (First Exploration for Hydrocarbons in the Countries of the Levant under French Mandate), by M. L. Dubertret. *Ann. Combus. Liquides*, No. 1 (Paris, January-February, 1935), pp. 31–53; 4 figs, 1 pl.

GENERAL

* *Introduction to Geology*, by E. B. Branson and W. A. Tarr. 470 pp., 456 figs. 6×9 inches. Cloth. McGraw-Hill Book Company, Inc., 330 West 42d St., New York (1935). Price, $3.75.

* "Volume, Shape, and Roundness of Quartz Particles," by Hakon Wadell. *Jour. Geol.* (Univ. Chicago), Vol. 43, No. 3 (April-May, 1935), pp. 250–80; 6 figs.

* "Structure and Creep," by Noel H. Stearn. *Ibid.*, pp. 323–27; 3 figs.

* "Sedimentary and Petrographic Analysis of the St. Peter Sandstone," by George A. Thiel. *Bull. Geol. Soc. America*, Vol. 46 (April 30, 1935), pp. 559–614; Pls. 45–48; 16 figs.

* *Petroleum Technical Review*, Vol. 1, No. 1 (April, 1935). 23 pp. (2 columns per page). Size, 8.75×11.625 inches. Paper. Bibliographic abstracts of world technical literature relating to geology, exploration, production, refining, marketing, and patents of petroleum and its products. A continuation and extension of the service formerly rendered by the U. S. Bureau of Mines. Issued monthly by the Oildom Publishing Company, 1217 Hudson Boulevard, Bayonne, New Jersey. Subscription, per year, $5.00.

* "Die bionomische Enteilung der fossilen Meeresböden" (The Bionomic Classification of the Fossil Marine Sediments), by Hermann Schmidt. *Fortschritte der Geologie und Palaeontologie*, Vol. 12, No. 38 (1935). Gebrüder Borntraeger, Berlin. 154 pp., 24 figs. Subscription price, 12.80 R.M.; price per single copy, 16 R.M.

* "Fortschritte der Ölgeologie" (Progress in Petroleum Geology), by Karl Krejci. *Geol. Rundschau* (Ferdinand Enke Verlag, Stuttgart), Vol. 26, No. 1–2 (1935), pp. 1–65, including bibliography of more than 300 subjects.

* "Future Crude Supplies Must Come from Reserves Not Yet Discovered," by William B. Heroy. *Oil Weekly*, Vol. 77, No. 6 (April 22, 1935) pp. 19–23; 4 figs.

* "Oil Fields of Gulf Coast Area Found in Sediments of Late Geological Age," by E. G. Woodruff. *Oil and Gas Jour.* (Tulsa, Oklahoma), Vol. 33, No. 46 (April 4, 1935), pp. 38–39, 149; 3 figs.

* "Oil Production: Analysis of Its Development and Stabilization," by Wallace E. Pratt. *Oil and Gas Jour.*, Vol. 33, No. 50 (May 2, 1935), pp. 17–18.

GEOPHYSICS

* "Electrical Prospecting Methods Demonstrated," by E. W. K. Andrau. *Oil and Gas Jour.*, Vol. 33, No. 46 (April 4, 1935), pp. 137–39; 2 figs.

* "Reflection Shooting by Geophysicist on Progress of His Art," by Robert P. Clark. *Ibid.*, pp. 129–31; 4 figs.

* "Übersichtstabelle der Methoden der angewandten Geophysik in der praktischen Geologie" (Tabular Review of Applied Geophysics in Economic Geology), by E. Hameister. *Zeit. prak. Geol.*, Vol. 43, No. 2 (February, 1935), pp. 26–29. Wilhelm Knapp in Halle, Saale.

* "Salt Domes—The Impetus to Geophysical Prospecting," by R. A. Steinmeyer. *Electrochemical Society* (Columbia University, New York) *Preprint 67–15* (March 25, 1935), pp. 161–73; 4 figs. Paper presented at 67th general meeting of the Society, New Orleans, March 21–23, 1935.

* "Some Practical Examples of Magnetic Prospecting," by W. P. Jenny. *Oil and Gas Jour.*, Vol. 33, No. 49 (April 25, 1935), pp. 33–34, 48; 8 figs.

GERMANY

* "Der Unterbau des Wiener Beckens," by L. Waagen. *Bohrtech. Zeit.* (Hans Urban, Vienna), Vol. 53, No. 4 (April 15, 1935), pp. 93–98.

IDAHO

"Miocene Plants from Idaho," by E. W. Berry, *U. S. Geol. Survey. Prof. Paper 185-E* (1935), pp. 97–125, Pls. 19–24, Figs. 4–5. For sale by Supt. Documents, Govt. Printing Office, Washington, D. C. Price, $0.10.

KANSAS

* "Limestone Reservoir Rocks of Kansas React Favorably to Acid Treatment," by C. E. Clason and John G. Staudt. *Oil and Gas Jour.*, Vol. 33, No. 49 (April 25, 1935), pp. 53–56, 58; 2 photos.

MONGOLIA

* "A Scheme of the Geological Structure of the Gobi-Altai Mongolian National Republic," by A. A. Maccaveev. *Problems of Soviet Geology* (Moscow), Vol. V, No. 1 (1935), pp. 9–25 in Russian, pp. 25–26 (English abstract), 11 figs.

* "New Data on the Geology of the Central Part of the Mongolian National Republic," by V. K. Tchaikovsky. *Ibid.*, pp. 27–50 in Russian, pp. 50–51 (English abstract), 4 figs.

NEW MEXICO

"Geology and Fuel Resources of the Southern Part of the San Juan Basin, New Mexico: Part 1, The Coal Field from Gallup Eastward toward Mount Taylor, with a Measured Section of Pre-Dakota (?) Rocks Near Navajo Church," by J. D. Sears. *U. S. Geol. Survey Bull. 860-A* (1935). 29 pp., 17 pls. (incl. 3 maps). For sale by Supt. of Documents, Govt. Printing Office, Washington, D. C. Price, $0.35.

PENNSYLVANIA

* "Subsurface Stratigraphy of Northwestern Pennsylvania and a Résumé of Gas and Oil Possibilities of Deeper Sands," by Charles R. Fettke. *Pennsylvania Top. and Geol. Survey Bull. 114* (Harrisburg, March, 1935). 23 pp., 4 illus.

"Somerset-Windber, Pennsylvania," by G. B. Richardson. *U. S. Geol. Survey Atlas Folio 224* (1935). 14 pp., 8 maps, 12 figs. For sale by U. S. Geol. Survey, Washington, D. C. Price, $0.50.

* "Possibility of Deep Production in Northwestern Pennsylvania," by C. R. Fettke and S. H. Cathcart. *Oil and Gas Jour.*, Vol. 33, No. 50 (May 2, 1935), pp. 19–20, 38–39; 4 figs.

POLAND

* *Industrie minière du Petrole en Pologne. Revue Annuelle, 1934* (Review of Petroleum Industry in Poland, 1934), by K. Tolwinski, Carpathian Geological Survey, Boryslaw, Poland (1935). 28 pp., approx. 9×12 inches, 42 tables, 14 figs. Contains a separate folded sheet in colors, "Geological Map of Rypne-Perehinsko," showing topographic and structural contours and areal geology. Sheet, 37.75×48 inches.

ROUMANIA

* "Nouvelles donées sur la structure du Bassin Transylvain" (New Facts on the Structure of the Transylvanian Basin), by D. T. Ciupagea. *Bul. Soc. Română de Geologie* (Bucarest), Vol. II (1935). Reprint, 32 pp., 2 maps, 4 geologic sections.

* "Die Salsen von Beciu-Berca, Rumänien" (The Mud Volcanoes of Beciu-Berca, Roumania), by Karl Krejci. K. Andree's *Geologische Charakterbilden No. 40* (1935). 22 pp., 8 pls. 9.5×12.75 inches. Paper. Gebrüder Borntraeger, Berlin, Germany.

TEXAS

"Artesian Water in Somervell County, Texas," by A. G. Fiedler. *U. S. Geol. Survey Water-Supply Paper 660.* 86 pp., 7 pls. (incl. 4 maps), 5 figs. For sale by Supt. Documents, Govt. Printing Office, Washington, D. C. Price, $1.15.

* "Excess Core Recovery in Southwest Texas," by Noel H. Stearn. *Oil Weekly* (Houston, Texas), Vol. 77, No. 4 (April 8, 1935), pp. 21–22; 1 fig.

VENEZUELA

* "Eastern Venezuela Expected to Become Major Producing Area," by George R. Pinkley. *Oil Weekly*, Vol. 77, No. 5 (April 15, 1935), pp. 37–39; 1 fig.

WEST INDIES

* "Alte Land- und Meeresverbindungen in West Indien und Zentralamerika" (Former Land and Sea Connections in the West Indies and Central America), by L. Rutten. *Geol. Rundschau* (Stuttgart), Vol. 26, No. 1–2 (1935), pp. 65–94; 3 figs. Bibliography of approx. 150 subjects.

PUBLICATIONS OF DIVISION OF PALEONTOLOGY AND MINERALOGY

* *Journal of Paleontology*, Vol. 9, No. 3 (April, 1935).

"Geological and Geographical Distribution of Reef Corals in Japan," by Hisakatsu Yabe and Toshio Sugiyama.

"New Middle Cambrian Agnostian Trilobites from Vermont," by B. F. Howell.

"Cambrian and Ordovician Trilobites from Herault, Southern France," by B. F. Howell.

"A New Ordovician Graptolite Locality in Utah," by T. H. Clark.

"New Mississippian Species of Strophalosia from Missouri," by Norman Hinchey and Louis L. Ray.

"A New Species of Haliotis from the Pliocene of Southern California," by H. E. Vokes.

"Pleistocene Mollusks from Western Cuba," by Horace G. Richards.

"Tertiary Insects of the Family Chrysopidae," by F. M. Carpenter.

"Ecology of Sand Areas," by W. H. Twenhofel.

"Paleozoic Foraminifera, their Relationships to Modern Faunas and to their Environment," by Joseph A. Cushman.

* *Journal of Sedimentary Petrology*, Vol. 5, No. 1 (April, 1935).

"Some Suggestions for Heavy Mineral Investigations of Sediments," by William M. Cogen.

"A Study of Some Great Basin Lake Sediments of California, Nevada and Oregon," by R. R. Shrock and A. A. Hunzicker.

"The Microflora of the Mud Deposits of Lake Mendota," by Fred T. Williams and Elizabeth McCoy.

"The Deep-Sea Bottom Samples Collected in the Pacific on the Last Cruise of the Carnegie," by Roger Revelle.

"Marine Erosion of Glacial Deposits in Massachusetts Bay," by H. C. Stetson and Marshall Schalk.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 19, NO. 6 (JUNE, 1935), PP. 920-924, 1 FIG.

THE ASSOCIATION ROUND TABLE

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The executive committee has approved for publication the names of the following candidates for membership in the Association. This does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it promptly to J. P. D. Hull, business manager, Box 1852, Tulsa, Oklahoma. (Names of sponsors are placed beneath the name of each nominee.)

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BIOGRAPHICAL SKETCHES OF NEWLY ELECTED HONORARY MEMBERS

Those not already well acquainted with the interesting careers of the two newly elected honorary members of the Association will doubtless be interested in the following brief biographical notes. The election this year of Gilbert D. Harris and Walter C. Mendenhall brings the total number of those having received this honor to sixteen. This award is made by the executive committee of the Association to "persons who have contributed distinguished service to the cause of petroleum geology."

GILBERT D. HARRIS

Gilbert D. Harris, professor emeritus of Cornell University, has made outstanding contributions in his work on the salt domes of the Gulf Coast area, and in his recognition and description of one of this country's most important structural features from an oil standpoint—the Sabine uplift of Louisiana and East Texas. He was among the first to use small fossils obtained from drill cuttings as an aid in determining subsurface correlations. His paleontological contributions have been remarkably extensive.

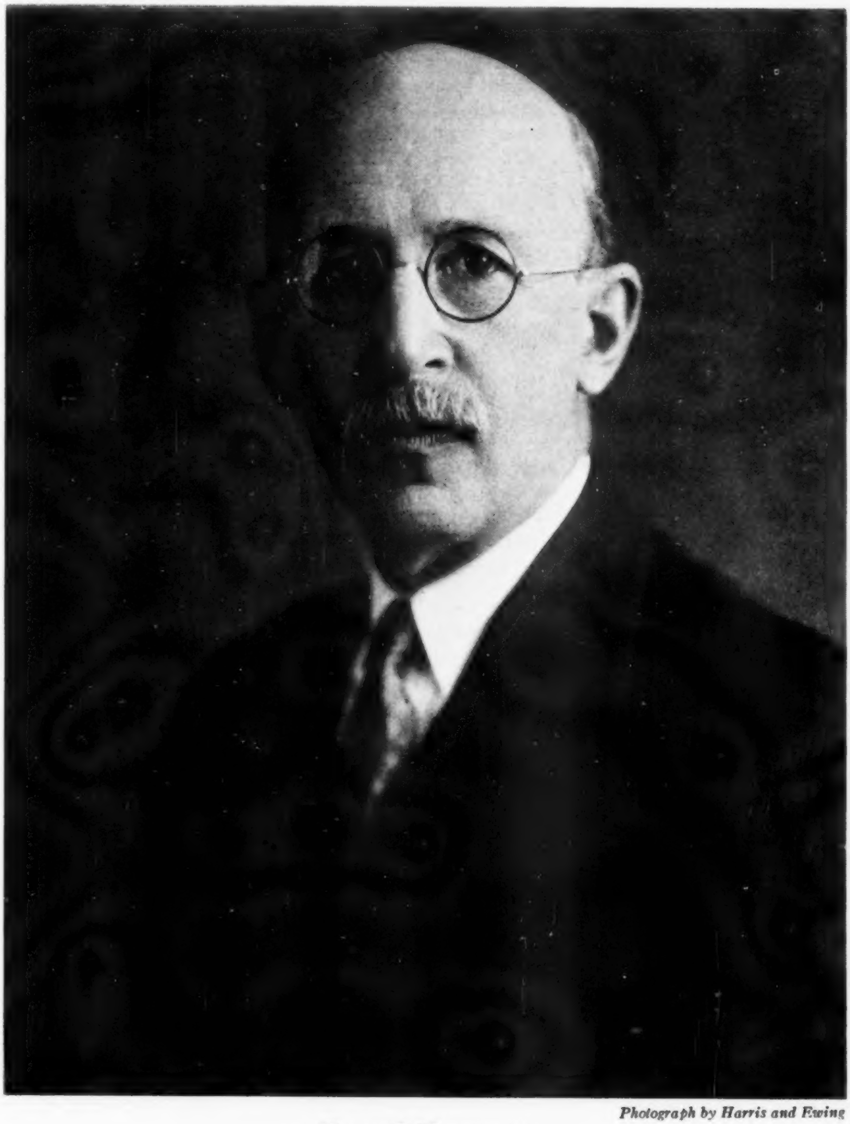
After completing post-graduate work in geology at Cornell University, Doctor Harris served on the Arkansas Geological Survey during 1887 and 1888, on the United States Geological Survey from 1888 to 1892, and on the Texas Geological Survey from 1892 to 1893. From 1894 to 1934 he taught paleontology, stratigraphy, and historical geology at Cornell University, and from 1898 to 1909 acted also as State geologist of Louisiana.

Professor Harris has written an extensive series of geological contributions dealing especially with the Tertiary formations of the Gulf and Atlantic Coast areas of the United States, many countries of South America, and the islands of the Caribbean region. His extensive paleontological collections also include much material from the Paleozoic of the northern Appalachian region and the Mesozoic of France. Certain of these collections, besides tertiary material, are considered the most complete in existence.

Just prior to his retirement from active teaching in 1934, Professor Harris established the Paleontological Research Institution, and with a group of assistants carries on at his "cabina," 126 Kelvin Place, Ithaca, New York. The results of his work for the most part have appeared in his Bulletin of American Paleontology and Paleontology Americana. His students and co-workers describe him as an untiring worker, a very inspiring teacher, and a most congenial companion in field work.

WALTER C. MENDENHALL

Dr. Walter C. Mendenhall, director of the United States Geological Survey, Washington, D. C., has been a member of the Survey since 1894, except for post-graduate work at Harvard (1896–97) and Heidelberg (1899–1900). His earlier university work was at Ohio Northern University. Much of Dr. Mendenhall's early professional work was in Alaska. From 1908–1912 he had charge of ground-water investigations in several of the western states and Hawaii. As chief of the Land Classification Board (1912–22) he supervised the selection and setting aside of our naval oil reserves and the leasing of public lands for oil, gas, and mineral development. He also supervised the



Photograph by Harris and Ewing

WALTER C. MENDENHALL

classification of coal-bearing areas and estimates of coal reserves. He served as chief geologist of the United States Geological Survey from 1922 to 1930, and supervised the preparation of many oil and gas reports, particularly of areas in Oklahoma, Wyoming, and California. In coöperation with the State agencies, he arranged for the compilation of geological maps of many states, including Oklahoma, Texas, and Arkansas. He has been director of the Survey since 1931, following two years as acting director.

Dr. Mendenhall, in serving as general secretary, contributed largely to the success of the Sixteenth International Geological Congress, held at Washington in 1933. A new geological map of the United States, and thirty guide books for geological excursions in the United States, were completed for this occasion. During 1934 he supervised the preparation of a very comprehensive review of the geology and occurrence of petroleum in the United States, included in Part 2 of the Petroleum Investigation Hearings, House Resolution 441, Seventy-Third Congress.

It seems most conservative to say that these two men have contributed distinguished service to the cause of petroleum geology.

MONROE G. CHENEY

COLEMAN, TEXAS
April, 1935

TWENTY-FIRST ANNUAL MEETING

TULSA, OKLAHOMA, MARCH 19, 20, and 21, 1936

At the invitation of the Tulsa Geological Society the twenty-first annual meeting of the Association will be held at Tulsa, Oklahoma, March 19, 20, and 21, 1936. Edward Bloesch, president of the Society, has appointed the following to make local arrangements for the meeting: Frank R. Clark, general chairman; W. B. Wilson, vice-chairman; and Ira H. Cram, vice-chairman in charge of the technical program.

Plans are being made to accommodate a large number of geologists, wives, and friends. The annual meeting held in Tulsa in 1927 holds the record of largest registered attendance of A.A.P.G. conventions—1,827 persons.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 19, NO. 6 (JUNE, 1935), 925-932, 1 FIG.

Memorial

DAVID WHITE

Dr. David White, an honorary member of The American Association of Petroleum Geologists, died February 7, 1935, in his 73d year. His life was characterized by enthusiastic, inspiring leadership and unstinting service to others and was crowded with outstanding achievements. He had much to do with the growth and expansion of the petroleum industry in the United States, and the influence of his ideas has been world-wide. The fields of his activity in geology were many. He gained the distinction of being the leading American authority on the fossil floras of Carboniferous age and on the origin and evolution of coal.

David White was born of early pre-Revolutionary stock, July 1, 1862, on a farm in Palmyra Township, Wayne County, New York, the youngest of eight children. He attended the country schools, where at times some of his older brothers and sisters were teachers. During his student days in the Collegiate Institute of Marion, 1 mile north of his home, he was influenced, by the deep scientific interest of the principal, Daniel Van Cruyningham, to study the systematic botany of the flowering plants of the region. After graduating from the Collegiate Institute, at the age of 18, he taught school for two winters, and then, having won a State scholarship to Cornell University, through a county competitive examination, he entered the university with the class of 1886.

He had almost no financial resources with which to go forward in his college work. He borrowed a little money from an elderly friend and neighbor and received some help from his eldest brother. The State scholarship he had won provided free tuition, and fortunately he was able to earn a considerable part of his college expenses by teaching elementary freehand drawing. White's instruction in drawing began in his freshman year, and by the end of his sophomore year he had been appointed assistant instructor under Professor E. C. Cleaves, then head of the drafting department. Among his students was George H. Ashley, now State geologist of Pennsylvania.

His college days were marked with a record of distinction and honor. At the end of the freshman year he was the only one in his class to receive "straight honorable" in every subject in the program of the entire year. He became one of the editors of the *Cornell Daily Sun* and was chief editor of the *Cornell Era*, the annual publication of the junior class. In his sophomore year he won the Andrew D. White prize, a cash honorarium, for the highest standing in veterinary science.

White's study of geology began in his sophomore year, when he took a course in general geology given by Samuel Gardner Williams. Later he had courses under Henry S. Williams and Charles S. Prosser. Although he took courses in vertebrate and invertebrate paleontology, his botanical training both at Marion and at Ithaca directed his main interest to fossil plants. In the course of field class work in collecting invertebrate fossils from the Devonian formations in the vicinity of Ithaca, numerous plant fragments were

Photograph by Bachrach

DAVID WHITE

gathered, and in these he was particularly interested. As his subject for the thesis then required for the B.S. degree, he chose the material described by Dawson as *Ptilophyton*, which is found abundantly in the shaly flags beneath the Cornell campus. The doubt remaining in his mind at the end of the work, as to whether the genus really represented an alga or a plant of any kind, proved 40 years later to have been well founded.

The many new and original drawings in the thesis kindled the interest of Henry S. Williams. Consequently, when Lester F. Ward, who was then in charge of paleobotanic investigations for the United States Geological Survey and who was in need of a great number of drawings of fossil leaves, wrote to Professor Williams in the spring of 1886 asking whether he had a student with a knowledge of fossils and also with the ability to make accurate if not artistic drawings, Professor Williams promptly recommended his student White. An invitation equally prompt was extended to White to fill the position under Professor Ward. Thus David White became a member of the United States Geological Survey, May 16, 1886. He was still a member of that organization at the time of his death. His entire scientific career of almost 49 years was therefore linked with the Geological Survey.

David White and Mary Elizabeth Houghton, of Worcester, Massachusetts, were married February 2, 1888. The bride, also of English stock dating back to Massachusetts colonial days, was a student at Sage College in Ithaca where the acquaintanceship began that ripened into that lifelong spiritual and intellectual companionship which David White always considered the greatest good fortune of his life.

After White joined the Geological Survey, he was from time to time assigned increasing responsibilities in his paleobotanic work. He early came to specialize in the practically unoccupied field of the Paleozoic plant life. His high standing as a stratigraphic paleobotanist rests primarily on his study of the Pottsville (Pennsylvanian) floras of the Appalachian region.

He revolutionized the then generally accepted concept according to which the Pottsville, the Allegheny, the Conemaugh, the Monongahela, and the Dunkard (Permian) were supposed to lie lengthwise throughout the Appalachian trough. He found that all the Pennsylvanian beds in Alabama, probably exceeding 10,000 feet in thickness, the entire Pennsylvanian of Tennessee, and all but a rather small part of the Pennsylvanian of the northeastern Kentucky coal field were of Pottsville age. The conclusiveness of his results was soon recognized by State officials, and his advice on the correlation of rocks and coal beds of this age was sought and accepted by State and Federal geologists alike.

Dr. White in 1910 was placed in charge of the section of eastern coal fields in the Geological Survey, a position that had become vacant through the appointment of Dr. George H. Ashley as State geologist of Tennessee. Two years later he was appointed chief geologist, and he served in that capacity from November 16, 1912, to November 16, 1922, when he was released at his own urgent request. During a part of this period he was also chief of the section of oil and gas fields. After his 10-year service as chief geologist, which included the period of the World War, 3 years were devoted to the chairmanship of the division of geology and geography of the National Research Council. Although the administrative duties that began in 1910 gave him excellent opportunities for the study and better understanding of the problems in-

volved in the geology and occurrence of coal and oil, they caused the almost complete cessation of his paleobotanic activity for about 15 years. This was a source of much regret to him.

While he was chief geologist his wise judgment and enthusiastic influence affected and shaped the geologic investigations of the Geological Survey. This was especially true of the World War period, when he tirelessly devoted time, energy, and thought to the interests of the United States and was a constant source of encouragement and inspiration to his associates.

The geologists of the Geological Survey, working under his direction, did pioneer work in the application of geologic methods to the search for oil and gas. The oil companies, having come to recognize the value of the application of geology in the search for oil, made large inroads on the Survey personnel immediately after the World War. Thus a notable proportion of the leading oil geologists of the world, on company payrolls, were former members of the staff of the United States Geological Survey. They carried with them into the commercial field the guiding scientific principles gained through investigation and experience under Dr. White's direction.

In the search for new methods to aid in the discovery of petroleum and thus to eliminate, so far as possible, the waste involved in drilling dry holes, he not only formulated new conclusions on the problems relating to oil, but he sought methods for guiding exploration. His interest in geophysical problems was first aroused in 1912. He was the first to apply gravimetry in the detection of anticlinal structure in this country. These applications were made in 1917 and 1919, when stations profiling Damon Mound, in Texas, and the folds of Pennsylvanian age in western Maryland were occupied by the Coast and Geodetic Survey, in compliance with a request from the Geological Survey, that originated with Dr. White. These observations antedated the introduction of the Eötvös torsion balance in the United States, in 1922, for the purpose of locating salt domes that might later be drilled for oil. The relations of these and other gravity observations to the geologic features of different parts of the United States were discussed in his presidential address[1] before the Geological Society of America, December 27, 1923.

Another method, suggested by him as of possible value in the search for oil, involved the determination of temperatures of the rock strata at depth. In accordance with this suggestion observations of temperatures in deep bore holes and mines were begun by the Geological Survey for the purpose of testing the hypothesis, maintained by some geologists, that oil- and gas-bearing formations have higher temperatures and offer steeper temperature gradients than formations not containing these hydrocarbons. The observations of temperatures have been conducted by many workers and have brought together basic scientific data of wide application to many problems of geology.

Dr. White's principal contribution to petroleum geology relates to the regional distribution of oil and is generally known as the "carbon-ratio theory." His conclusions were formulated in connection with his studies of the coals and the oil and gas deposits and of their relations in the Appalachian

[1] "Gravity Observations from the Standpoint of the Local Geology," *Bull. Geol. Soc. America*, Vol. 35 (1924), pp. 207–77.

and Mid-Continent regions. They are here stated in his own words,[2] as expressed 20 years ago.

> In regions where the progressive devolatilization of the organic deposits in any formation has passed a certain point, marked in most provinces by 65 to 70 percent of fixed carbon (pure-coal basis) in the associated or overlying coals, commercial oil pools are not present in that formation nor in any other formations normally underlying it, though commercial gas pools may occur in a border zone of higher carbonization. The approximate carbonization limits of the rocks containing or overlying oil pools may be found to vary somewhat in different provinces according to the characters of the original organic debris, the circumstances attending its deposition, and the geologic structure.
>
> Wherever the regional alteration of the carbonaceous residues passes the point marked by 65 percent or perhaps 70 percent of fixed carbon in the (pure) coals, the light distillates appear, in general, to be gases at rock temperatures. Occluded oils may, in some cases, have escaped volatilization.

The conclusions, as quoted, with others, were embodied in his address in 1915 as retiring president of the Washington Academy of Sciences. Appearing in the proceedings of a local society, they did not attract the attention of the profession until M. L. Fuller, some years later, called attention to Dr. White's paper and to the application of his conclusions to the Texas-Oklahoma region. Since then they have become almost universally accepted, with consequent lessening of the annual waste of money and effort by companies that persisted in drilling for oil in areas in which the carbonization is distinctly too far advanced.

As a preparedness measure, field investigations of the vast deposits of oil shales in Colorado, Utah, and Wyoming were begun in 1913, in anticipation of the day when it might be commercially profitable to utilize some of the enormous supply of petroleum to be derived from the deposits. As pointed out at that time by Dr. White, no prediction could be made concerning the date when it would be necessary to draw rapidly from this source.

Early in the World War he recognized the apparent inadequacy of the available supply of petroleum to meet the demands for war purposes. Attention was therefore directed by the Geological Survey to this vital question, and every available oil and coal geologist on the Survey's staff was assigned to conduct geologic studies in known or prospective petroleum regions, where increased production could be expected to follow geologic exploration.

At the same time the necessity for conserving our available supply of petroleum was obvious. Accordingly, with conservation as the principal objective, estimates of the petroleum reserves of the United States were prepared from time to time between 1916 and 1922, under the direction of Dr. White. One of the estimates—that compiled in 1921—was prepared jointly by the Geological Survey and The American Association of Petroleum Geologists; the others were prepared by the Geological Survey. For comparative purposes, an estimate of the petroleum resources of the world was compiled in 1920 by Dr. White and Eugene Stebinger. As he pointed out at that time,

> The submission of carefully prepared estimates of the oil reserves of the United States calls for no apology or explanation. In this country petroleum is a rapidly wasting asset, and an occasional appraisal of the amount remaining in the ground is a simple business procedure to safeguard the general welfare and the prosperity of the Republic.

[2] *Jour. Washington Acad. Sciences*, Vol. 5, No. 6 (March 19, 1915), p. 212.

Another prime motive for the compilation of the estimates was to arouse a realization by the United States Government of the need for obtaining petroleum reserves, on which the United States might depend when its then known reserves should reach exhaustion. There was also a hope that publicity of the estimates would stimulate American oil companies to search for and secure undeveloped reserves abroad. These objectives were realized. In the light of the subsequent production of petroleum and the estimates of reserves appearing after 1922, it is obvious that the estimates of 1922 and earlier years were conservative, even if allowance is made for later improvements in methods of recovery and great increases in depths explored; but the effects and purposes of the earlier estimates have directed public attention to the problem and sharpened the vision of those engaged in development.

The active participation of Dr. White in problems relating to petroleum was maintained during his term as chairman of the division of geology and geography of the National Research Council, for the 3 years, 1924–27. While occupying this position he was the guiding spirit in outlining a program of fundamental research in petroleum that was undertaken by the American Petroleum Institute, with the advice and assistance of the central petroleum committee of the National Research Council. In addition, his counsel aided in obtaining, on November 1, 1925, $250,000 from John D. Rockefeller and, in January, 1926, a like amount from the Universal Oil Products Company, for research in petroleum geology. This half million dollars was made available for supporting a 5-year program of research for the period July 1, 1926, to June 30, 1931. This large program was wide in its scope. Altogether 40 projects were instituted that could be grouped into two classes: those pertaining to the origin and recovery of petroleum, and those pertaining to the composition and properties of petroleum. Dr. White served not only as a member of the central petroleum committee for the guidance of these investigations but also as director or adviser for some of the projects.

Because his long and active career as a geologist was thus linked with the phenomenal growth of the American petroleum industry and with the equally phenomenal growth of the importance of petroleum geology, it was especially fitting that he was requested, in 1934, by the Director of the United States Geological Survey, to prepare for the official use of a subcommittee of the Committee on Interstate and Foreign Commerce, House of Representatives, Seventy-Third Congress (recess), a report on the outstanding features of petroleum development in America and on the origin of petroleum. This report formed a portion of the material that was submitted by the Geological Survey to the subcommittee and was published in 1934, in Part 2 of the Hearings conducted by the subcommittee under House Resolution 441. Dr. White's contribution on the petroleum development in America has been reprinted in the *Bulletin* of The American Association of Petroleum Geologists for April, 1935, in order to make it more generally available.

The last 7 years of his life, during which the heavy load of administrative duties and committee assignments had been lightened, was devoted, with full vigor and enthusiasm, to research and to the preparation of papers in the fields that he had had little opportunity to touch for many years. In 1931 he suffered a serious physical breakdown but, although recovery only partly restored his physical endurance, his mental powers were entirely unimpaired. With will power and enthusiasm which rose above circumstances that would

be well-nigh insuperable to others, he completed most of the important researches that he had earlier planned. Only a few days before his death he completed a paper reviewing and bringing up to date the discussion of the carbon-ratio theory, his important contribution made 20 years earlier. The new paper, entitled "Metamorphism of Organic Sediments and Derived Oils," has been published in the *Bulletin* of The American Association of Petroleum Geologists for May, 1935.

The broad scope of his fields of activity and the productive energy devoted to them are shown by the almost 200 titles in his bibliography.

Because of his distinguished services in the field of petroleum geology, he was elected, 15 years ago, to honorary life membership in The American Association of Petroleum Geologists; in 1931 he was awarded the Penrose medal by the Society of Economic Geologists, of which he was an organizer and charter member; and in 1934 he received the Boverton Redwood medal from the Institution of Petroleum Technologists of London. In recognition of his services in the field of paleobotany, he received from the National Academy of Sciences the Mary Clark Thompson medal and the Walcott medal, and he was elected to honorary membership in the geological societies of Belgium and China. He received honorary degrees from the universities of Cincinnati and Rochester in 1924 and from Williams College in 1925.

He was research associate, Carnegie Institution; curator of paleobotany, United States National Museum, since 1903; home secretary, National Academy of Sciences, July 1, 1923 to June 30, 1931, and vice-president, July 1, 1931, to June 30, 1933; member of executive board, National Research Council; president of the Geological Society of America, of the Geological Society of Washington, and of the Washington Academy of Sciences. Societies not already mentioned to which he was elected as a member include the Paleontological Society of America, Botanical Society of America, American Institute of Mining and Metallurgical Engineers, American Philosophical Society, and American Academy of Arts and Sciences.

Many honors thus came to him as a fitting reward for the full measure of industry, accomplishments, and helpfulness that he crowded into his life, his work being continued even through the day before the sleep from which he did not waken.

This biography, devoted chiefly to Dr. White's work in petroleum geology, is written from the viewpoint of a follower rather than that of a colleague. Like hundreds of other geologists younger than Dr. White, I came many years ago under his influence and was always inspired by his knowledge, enthusiasm, and constructive suggestions about the problems in hand. He never disorganized or discarded the results of other workers but always offered suggestions for improvement and especially for the pursuit of new lines of attack. He expected the workers he supervised to give their best efforts and to achieve the maximum results. Anything less than this did not attain his standard for accomplishment.

WASHINGTON, D. C. — HUGH D. MISER
March 18, 1935

APPRECIATION OF DOCTOR DAVID WHITE

Most sciences and professions are built around the works and accomplishments of the men engaged in those sciences and professions. The works of

some are so enthusiastic and complete as to become fundamental. Such were the works of Doctor David White in the science of geology. And, although his hands are now stilled, his eyes now closed and his lips now sealed in death, his works will live on as long as the rocks stand which he loved and studied. His name will be on the tongues of generations yet unborn.

Early in his career, he entered upon a study of the then great unknown field of Paleobotany with the spirit of an intrepid explorer. There were few mileposts of previous works along the way to guide him. That did not daunt him. He had a goal to attain, and steadily pushed on toward it. Little by little he gradually assembled materials from all parts of this continent and the world, and by painstaking study brought an understandable order out of what had hitherto been chaos. So great were his accomplishments in the study of fossil plants, that for many years past he has been recognized as an outstanding international authority on paleobotany. Universities of higher learning and academies of science throughout the world have honored him—justly.

We who are occupied in the study of petroleum geology here in Oklahoma owe Dr. White a debt not easily repaid. Always interested in problems of stratigraphy, of whatever nature, he has had a definite part in untangling many of the more complex problems of the geology of this state. But along another line of investigation he has probably been of greater service. This is along the line of his investigation into the nature and genesis of petroleum. It is indeed unfortunate that these studies were initiated so late in his life, for, although progress has been made, they remain incomplete. The foundation has been laid, however, and, although the work must now be carried on by understudies, it can be confidently expected that a solution of this most perplexing problem will emanate from the groundwork laid by Dr. White.

To enumerate even the subjects of his writings would unduly burden you. All categories of geology are included. Who among us has not read after him with wonder and appreciation of his breadth of knowledge and depth of understanding?

To express our appreciation of Dr. White solely as a scientist would be a half-hearted gesture and would fail to distinguish him above many others. As a man he was as truly great as he was as a scientist. True greatness is always couched in humility and service to others. These qualities characterized "Dr. David." He met life with a smile as wholesome and heartening as spring sunshine. To help another seemed his greatest joy. He was the friend of all. No beginner was too obscure or his problem too insignificant to receive tolerant, helpful and inspiring consideration from Dr. White. The most complicated and intricate theories of the most learned received his earnest, helpful consideration as well. Both were opportunities for service and he gave the best he had, freely and gladly, never seeking for himself anything more than the satisfaction of having helped a fellow man.

How then shall we evaluate the life of such a man? We can hardly do it, for the span of life is too short to count the harvest. We can only bow before the will of the Great Almighty. "By their works ye shall know them."

THE OKLAHOMA CITY GEOLOGICAL SOCIETY

OKLAHOMA CITY, OKLAHOMA
March 11, 1935

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 19, NO. 6 (JUNE, 1935), PP. 933-934

AT HOME AND ABROAD

CURRENT NEWS AND PERSONAL ITEMS OF THE PROFESSION

WILLIAM R. LONGMIRE has moved from the Wichita, Kansas, office of the Gypsy Oil Company to join the general geological staff at Tulsa, Oklahoma.

ANTHONY FOLGER has been promoted to take charge of the Wichita, Kansas, office of the Gypsy Oil Company, taking the place of William R. Longmire.

OSCAR HATCHER and MAURICE R. TEIS are in the employ of E. H. Moore, Inc., in the Ada district (Fitts area) of Oklahoma.

FRANK RINKER CLARK, chief geologist of the Marathon Oil Company of Tulsa, Oklahoma, has been appointed by President Levorsen to be chairman of the Association's committee on applications of geology, succeeding FREDERIC H. LAHEE, chief geologist of the Sun Oil Company, Dallas, Texas.

H. S. MCQUEEN, assistant State geologist of Missouri, Rolla, Missouri, has accepted membership in the committee on applications of geology, succeeding H. A. BUEHLER, State geologist of Missouri.

E. H. FINCH, of the Venezuelan Petroleum Corporation, 45 Nassau Street, New York, returned from South America last April.

P. E. FITZGERALD, of Dowell, Incorporated, has been transferred from Shelby, Montana, to the Tulsa, Oklahoma, district of the company.

CLYDE M. BENNETT, vice-president and assistant manager of production of the Magnolia Petroleum Company, Dallas, Texas, died on April 25.

PHIL K. COCHRAN, district geologist for the Carter Oil Company at Wichita, Kansas, has announced the transfer of D. A. HOLM from Ada, Oklahoma, to Wichita.

GLEN M. RUBY, ROBERT B. MORAN, E. R. READ, ROBIN WILLIS, C. S. DEMONBRUN, GRAYDON OLIVER, and R. D. SKELLEY have been elected directors of the Nordon Corporation.

L. H. FREEDMAN, formerly of Fort Worth, Texas, represents the Snowden-McSweeney Pipe Company at Mount Pleasant, Michigan.

R. DECHICCHIS, geologist, formerly with the Southern Crude Oil Purchasing Company, and ALLEN HARGRAVE, land man, formerly with the Simms Oil Company, have opened partnership offices at Midland, Texas.

JAMES L. TATUM, consulting geologist, has headquarters at McAllen, Texas.

GAYLE SCOTT, of Texas Christian University, Fort Worth, Texas, secretary-treasurer of the Society of Economic Paleontologists and Mineralogists,

and MAYNARD P. WHITE, of the Gypsy Oil Company, Ardmore, Oklahoma, are the two representatives of the Division of Paleontology and Mineralogy on the general business committee of the Association.

The Dallas Petroleum Geologists, of which L. J. PEPPERBERG is chairman and CHARLES B. CARPENTER is secretary-treasurer, has joined the group of geological societies affiliated with the Association.

V. H. Moscosso, of the Mexican National Railways, addressed the North Texas Geological Society, May 2, at Wichita Falls, Texas, at a special meeting which included as guests the wives and friends of members, on the beauties and points of interest in his country.

JOHN B. LUCKE, geologist for The Texas Company in the Panhandle district, left the company in June to join the Soil Erosion Service of the United States Department of Agriculture at New Brunswick, New Jersey.

R. B. MITCHELL, formerly district geologist for the Stanolind Oil and Gas Company at Pampa, Texas, has been transferred to the company's office at Tyler, Texas, where he is district geologist. GENTRY KIDD has been transferred from Midland, Texas, and now is district geologist at Pampa.

CHARLES HOOKWAY has been transferred from the Wichita Falls office of the Magnolia Petroleum Company to Amarillo, Texas, where he is now district geologist.

CHARLES N. GOULD spoke before the Tulsa Geological Society meeting April 15 at 8 P.M. on "Oklahoma Mineral Resources Other than Oil and Gas." On May 6 C. G. STRACHAN presented a paper entitled, "Pre-Pennsylvanian Channels in Western Kentucky and Relation to Oil Production," before the Society.

J. D. MCCLURE has joined the geological staff of the Barnsdall Oil Company at Tulsa, Oklahoma.

R. E. MINNES, formerly with the Shell Petroleum Corporation, is now employed by the Tide Water Oil Company at Tulsa, Oklahoma.

At the regular meeting of the Rocky Mountain Association of Petroleum Geologists on April 15, the following papers were presented: "Elk Mountains Region," by J. W. VANDERBILT, and "Ouray and Sangre de Christo Regions," by W. S. BURBANK. At the last meeting of the season on May 6, DART WANTLAND presented a paper entitled, "Applications of Resistivity Measurements to Highway and Other Engineering Problems."

EDWARD A. MAYER, who received the degree of Master of Arts from the University of Wisconsin in 1934, is employed in the geological department of the Shell Petroleum Corporation, with headquarters at Tulsa, Oklahoma.

At the annual meeting of the Panhandle Geological Society, held April 18, 1935, the following officers were elected for the new year: president, C. C. ANDERSON, U. S. Bureau of Mines, Amarillo Helium Plant, Amarillo; vice-president, W. W. RUSK, Amarillo Oil Company, Amarillo; secretary-treasurer, JOHN E. GALLEY, Shell Petroleum Corporation, Amarillo, Texas.

JEROME S. SMISER may be addressed in care of the Salt Dome Oil Corporation, 2600 Esperson Building, Houston, Texas.

NEVIN M. FENNEMAN, president of the Geological Society of America, has appointed FRANK R. CLARK, chief geologist of the Marathon Oil Company, Tulsa, Oklahoma, to be a member of the society's committee for publicizing geology, of which committee Carey Croenis, of the University of Chicago, is chairman. Clark is chairman of the Association's committee on applications of geology.

A regional meeting of the American Institute of Mining and Metallurgical Engineers will be held in San Francisco, California, October 3 and 4. The Petroleum Division of the Institute will meet in Houston, Texas, October 11 and 12.

The International Congress of Mining, Metallurgy, and Applied Geology will meet at Paris, France, October 20–26, 1935. Papers may be submitted to E. G. LEONARDON, Esperson Building, Houston, Texas.

The sixteenth annual meeting of the American Petroleum Institute will be held at Los Angeles, California, November 11–14.

JAMES H. GARDNER, on a visit to Kentucky in May, made an address on the 10th to the Anthropological Society of the University of Kentucky on the subject "Ancient Mounds at Spiro, Oklahoma." On the 8th he lectured to the students in geology at the university on the general subject of petroleum geology in the Mid-Continent area.

CHARLES T. LUPTON, consulting geologist of Denver, Colorado, died at the age of 57 years, May 8, 1935.

LEO S. FOX, acting chief geologist for the General Petroleum Corporation, Los Angeles, California, was killed in an automobile accident, May 5.

JOHN B. LUCKE presented a paper on "Ancient and Present Shore Lines," and HENRY ROGATZ presented his paper on "Subsurface Geology of the Texas Panhandle," before the Panhandle Geological Society, April 25, at Amarillo, Texas.

JAMES L. BALLARD, of the Stanolind Oil Company, has been transferred from Shawnee, Oklahoma, to the San Antonio, Texas, office of the company.

At the meeting of the San Antonio Geological Society, San Antonio, Texas, May 27, Edgar Tobin of the Edgar Tobin Aerial Surveys presented a paper on "The Science of Aerial Photography and Its Relation to Geology," after the dinner at the Petroleum Club. The date of the monthly meeting has been changed from the first Monday night to the third Monday night of each month. The Society decided to hold its seventh annual meeting on October 16 and 17, 1935, in Mexico City.

The 17th session of the International Geological Congress is to be held in Moscow in August, 1937. The organization committee, of which I. M. GOUBKIN is president and A. E. FERSMAN is general secretary, may be ad-

dressed: Moscow 4, Kotelnicheskaya Naberezhnaya, 17. The first circular of the committee, dated January, 1935, announces the following topics for discussion: (1) Problems of petroleum and petroleum resources of the world, (2) Geology of coal fields, (3) Pre-Cambrian and mineral deposits in regions of its expansion, (4) Permian system and its stratigraphical position, (5) Correlation of tectonic processes, magmatic formations, and ore deposits, (6) Tectonic and geochemical problems of Asia, (7) Deposits of rare elements, (8) Geophysical methods in geology, (9) History of geological knowledge. The official languages, as announced, are English, French, and Russian. It is planned to organize five excursions of 15–28 days each before the session: (1) Northern, (2) Ural, (3) Southern, (4) Volga, (5) Caucasus. During the session short excursions of 1–2 days will be arranged. After the session four long excursions of 40–50 days each will be offered: (1) Petroleum and geological stratigraphical, (2) Central Asia, (3) Transcontinental, (4) Turkestan-Siberia.

MID-YEAR MEETING, MEXICO CITY, OCTOBER 16–17, 1935

SEVENTH ANNUAL MEETING, SAN ANTONIO SECTION

The San Antonio Geological Society has announced that its seventh annual meeting will be held in Mexico City on October 16 and 17, 1935. The executive committee of The American Association of Petroleum Geologists has officially designated the Section meeting as the Mid-Year Meeting of the Association.

As this issue of the *Bulletin* goes to press, the plans of the committee on arrangements are not fully available, but Joseph M. Dawson, president of the San Antonio Section, states that a circular giving all details as to time, costs, transportation, program, points of interest, et cetera, is being prepared for mailing to each member of the Association. In October it is expected that the weather and countryside will be favorable and beautiful, the national automobile highway from Laredo to Mexico City will be completed and in good condition, and Mexico City hotels will not be overcrowded.

It is urged that vacations be planned now for this period. Those who desire to drive are advised that Mexico City is 767 miles from Laredo, Texas, or a drive of two days. The San Antonio Section is not planning to go in a body, as hotel accommodations along the way are not sufficient at this time to handle this large crowd. It is anticipated that many members will drive down two or three days ahead of time and spend longer in Mexico City than the actual dates of the convention, though only one week is required for the entire round trip (including the meeting) from the San Antonio district.

Geologists and officials in Mexico are giving the South Mid-Continent and Gulf Coast members enthusiastic support and approval, and judged by interested inquiries received during the past year from members in California, Kansas, and New York, the attendance at this meeting will make it an outstanding event in Association affairs. The last A.A.P.G. mid-year meeting was held in New York City in November, 1926.

For details write to Joseph M. Dawson, president, San Antonio Geological Society, 1105 Alamo National Building, San Antonio, Texas.